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HISTORICAL, PHYSICAL, AND CHEMICAL LIMNOLOGY OF TWIN LAKES, COLORADO

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16. ABSTRACT

The present study is an attempt to quantify the impacts of construction and operation of a pumped-storage powerplant on a montane lake environment by means of detailed investigations of the pre- and post-operation limnology of Twin Lakes, Colorado. This report covers a 5-year study of the preoperation physical and chemical limnology of the lakes and includes a summary of earlier limnological work by such investigators as Chauncey Juday, David Starr Jordan, F. V. Hayden, and John Wesley Powell.

Twin Lakes are a pair of second-class dimictic, connected, montane, drainage lakes of glacial origin. Chemically, Twin Lakes are soft, dilute calcium bicarbonate lakes with large accumulations of heavy metals, including iron, manganese, zinc, copper, and lead, in the bottom sediments. During periods of thermal stratification, hypolimnetic oxygen may become depleted to such an extent that reducing conditions at the sediment-water interface allow significant quantities of these metals to diffuse into the water column. This condition is especially pronounced during severe winters in the upper lake, apparently as a direct result of the higher oxygen demand of allochthonous organic matter deposited on the bottom of the upper lake since the turn of the century. The authors hypothesize a state of "trophic disequilibrium" in the upper lake and describe an experiment to test this hypothesis by winter oxygenation of the hypolimnion which began during the winter of 1976-77.

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by
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September 1977

Applied Sciences Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

This report was developed as a part of the Bureau of Reclamation's Twin Lakes Ecological Study (DR-331), which is being performed under the supervision of N. E. Otto, Head, Environmental Sciences Section, and L. O. Timblin, Jr., Chief, Applied Sciences Branch. The study is a cooperative effort involving the Bureau of Reclamation, Colorado Division of Wildlife, and the Fish and Wildlife Service's Colorado Cooperative Fishery Research Unit at Colorado State University. Some funding and field support were provided by the Lower Missouri Region and the Fryingpan-Arkansas Project of the Bureau of Reclamation.

Dr. D. A. Hoffman, formerly of the Bureau of Reclamation, initiated the Twin Lakes Ecological Study in 1971. The Physical Sciences and Chemical Engineering Section of the Bureau's Division of General Research has provided laboratory chemical and petrographic analyses for the study since its inception. The following individuals within the Bureau's Engineering and Research Center have made substantial contributions to this work: R. A. Roline, Biological technician; W. M. Batts, Photographer; M. A. Pederson, Librarian; K. D. Mahnken, W. J. Boegli, and W. F. Lorenz, Rotation engineers; J. M. Tilsley and Edna Hunsinger, manuscript review.

Valuable assistance in the field was rendered by W. R. McCormick of the Fryingpan-Arkansas Project and by L. M. Finnell and G. A. Bennett of the Colorado Division of Wildlife. Finally, the cooperation and assistance of several residents of the area are gratefully acknowledged.

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CONTENTS—Continued

APPLICATION

Results of this study will be of interest to anyone involved in the study of lake ecosystems, particularly those in mountainous regions. Considerable attention has been devoted to the role of sediment-water interactions in determining the tropic levels of the lakes.

Physical and chemical data obtained in this study will be used in conjunction with biological data to provide baseline information for determining the effects of the construction and operation of the Mt. Elbert Pumped-Storage Powerplant on Twin Lakes, Colo. Final results of this study will be combined with those from Banks Lake, Wash., the Salt River Project lakes, Ariz., and other locations, in a general assessment of the environmental effects of pumped-storage development over the range of climatic conditions encountered in the Bureau of Reclamation's area of operations.

INTRODUCTION

Over the past 20 years, pumped-storage powerplants have become increasingly important in the production of electrical power throughout the world. The ability of this type of plant to store energy during offpeak hours for use during periods of high demand and the declining availability of conventional hydroelectric sites have been the major reasons for this growth in importance.

Environmental impacts of these power operations are relatively unknown. The present research project is an attempt to quantify impacts on a mountain lake environment by means of detailed investigations of the pre- and postoperation limnology. This nearly 5-year study is unique among recent investigations of environmental effects of pumped-storage developments in both its emphasis on a high mountain lake and the length of preoperation study.

The research project centers on the Mt. Elbert Pumped-Storage Powerplant, now under construction at Twin Lakes, about 24 km (15 m) southwest of Leadville, Colo. This 200-MW plant is part of the Bureau of Reclamation's Fryingpan-Arkansas Project (fig. 1). Initial operation of the first of two 100-MW pump-generators is expected to take place in late 1977.

Investigations of the preoperation limnology of Twin Lakes began in May 1971 in cooperation with the Colorado Division of Wildlife and, later, the U.S. Fish and Wildlife Service's Colorado Cooperative Fishery Research Unit at Colorado State University. The Twin Lakes studies are also being coordinated with similar investigations at Banks Lake, Wash., and the Salt River Project lakes, Ariz., in an effort to generalize results over the range of environments encountered in the USBR's (Bureau of Reclamation's) operations. This report, detailing the preoperation physical and chemical limnology of Twin Lakes, Colo., is one in a series of reports emanating from these various studies.

GENERAL DESCRIPTION

Location

Twin Lakes is located on Lake Creek at the eastern foot of the Sawatch Range in the Upper Arkansas River Valley of central Colorado (fig. 2). The lakes are 2802 m (9193 ft) above mean sea level at 39°05' N. latitude and 106°20' W. longitude. This area is part of the Southern Rocky Mountain Physiographic Province and the vegetation around the lakes is generally characteristic of the Montane or Canadian Life Zone (Weber [1],[1] Moenke [2], Pennak [3]).

Origin

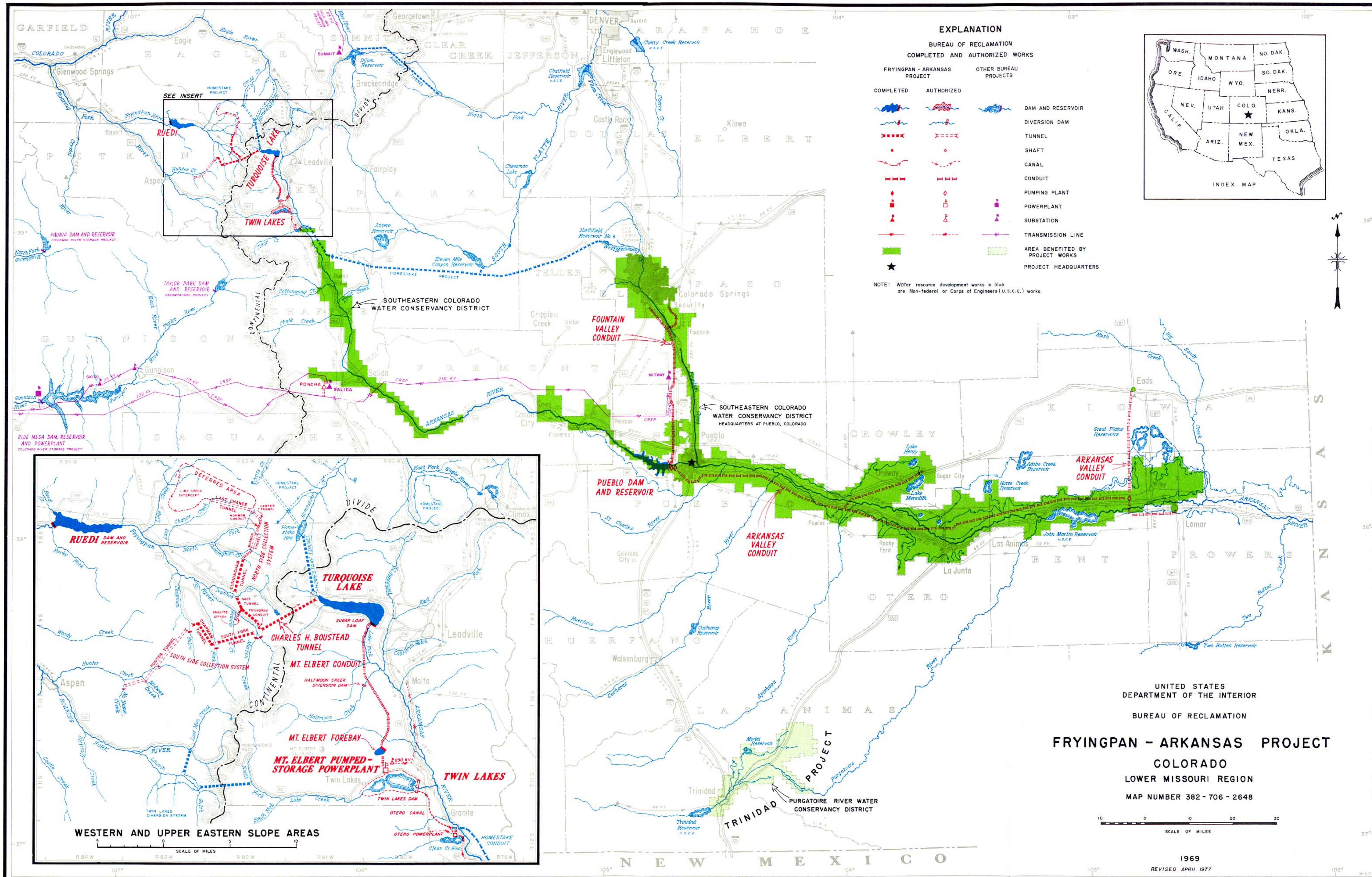
The present topography of the western side of the Arkansas River Valley in the Twin Lakes area is largely the result of glacial action on earlier alluvial deposits (Buckles [4]). The peaks of the Sawatch Range and the stream valleys at their base are markedly glaciated.

Twin Lakes probably originated with the morainic damming of Lake Creek, type 30a in Hutchinson's [5] classification of lake basins. Moraines are prominent today around the eastern shores of the lower lake and along the low ridge separating the upper and lower lakes.

Morphometry

The bottom topography and shoreline of Twin Lakes are shown on figure 3. Present maximum water surface elevation in both lakes is 2802 m (9193 ft) above mean sea level. Maximum surface areas are about 263.4 ha (651 acres) for the upper lake and 736.5 ha (1820 acres) for the lower, with corresponding maximum depths of about 28 m (92 ft) and 27 m (89 ft), respectively. Area-capacity data for Twin Lakes are

[1] Numbers in brackets refer to items in the Bibliography.


EXPLANATION
BUREAU OF RECLAMATION
COMPLETED AND AUTHORIZED WORKS
FRYINGPAN - ARKANSAS PROJECT
OTHER BUREAU PROJECTS
COMPLETED
AUTHORIZED
DAM AND RESERVOIR
DIVERSION DAM
TUNNEL
SHAFT
CANAL
CONDUIT
PUMPING PLANT
POWERPLANT
SUBSTATION
TRANSMISSION LINE
AREA BENEFITED BY PROJECT WORKS
PROJECT HEADQUARTERS
NOTE: Water resource development works in blue are Non-federal or Corps of Engineers (U.S.C.E.) works.
INDEX MAP
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
FRYINGPAN - ARKANSAS PROJECT
COLORADO
LOWER MISSOURI REGION
MAP NUMBER 382 - 706 - 2648
SCALE OF MILES
1969
REVISED APRIL 1977
SOUTHEASTERN COLORADO WATER CONSERVANCY DISTRICT
SOUTHEASTERN COLORADO WATER CONSERVANCY DISTRICT HEADQUARTERS AT PUEBLO, COLORADO
FOUNTAIN VALLEY CONDUIT
PUEBLO DAM AND RESERVOIR
ARKANSAS VALLEY CONDUIT
TRINIDAD PROJECT
PURGATOIRE RIVER WATER CONSERVANCY DISTRICT
RUEDI
TURQUOISE LAKE
TWIN LAKES
SEE INSERT
WESTERN AND UPPER EASTERN SLOPE AREAS
RUEDI DAM AND RESERVOIR
CHARLES H. BOUSTEAD TUNNEL
MT. ELBERT CONDUIT
MT. ELBERT FOREBAY
MT. ELBERT PUMPED-STORAGE POWERPLANT
SOUTH SIDE COLLECTION SYSTEM
NORTH SIDE COLLECTION SYSTEM
HALFMOON CREEK DIVERSION DAM
TWIN LAKES DAM
OTERO CANAL
OTERO POWERPLANT
HOMESTAKE CONDUIT
NEW MEXICO
KANSAS

GPO 840-550

Figure 2.—View of Twin Lakes, Colo., looking west. (Photo No. P382 706 2742 NA)

ELEVATIONS	
FEET	METRES
9105	2775.2
9110	2776.7
9115	2778.2
9120	2779.8
9125	2781.3
9130	2782.8
9135	2784.3
9140	2785.9
9145	2787.4
9150	2788.9
9155	2790.4
9160	2792.0
9165	2793.5
9170	2795.0
9175	2796.5

NOTES

Contours below EL. 9175 based on soundings made 4-14-64 to 4-23-64.

(2) Approx. location of data collection stations

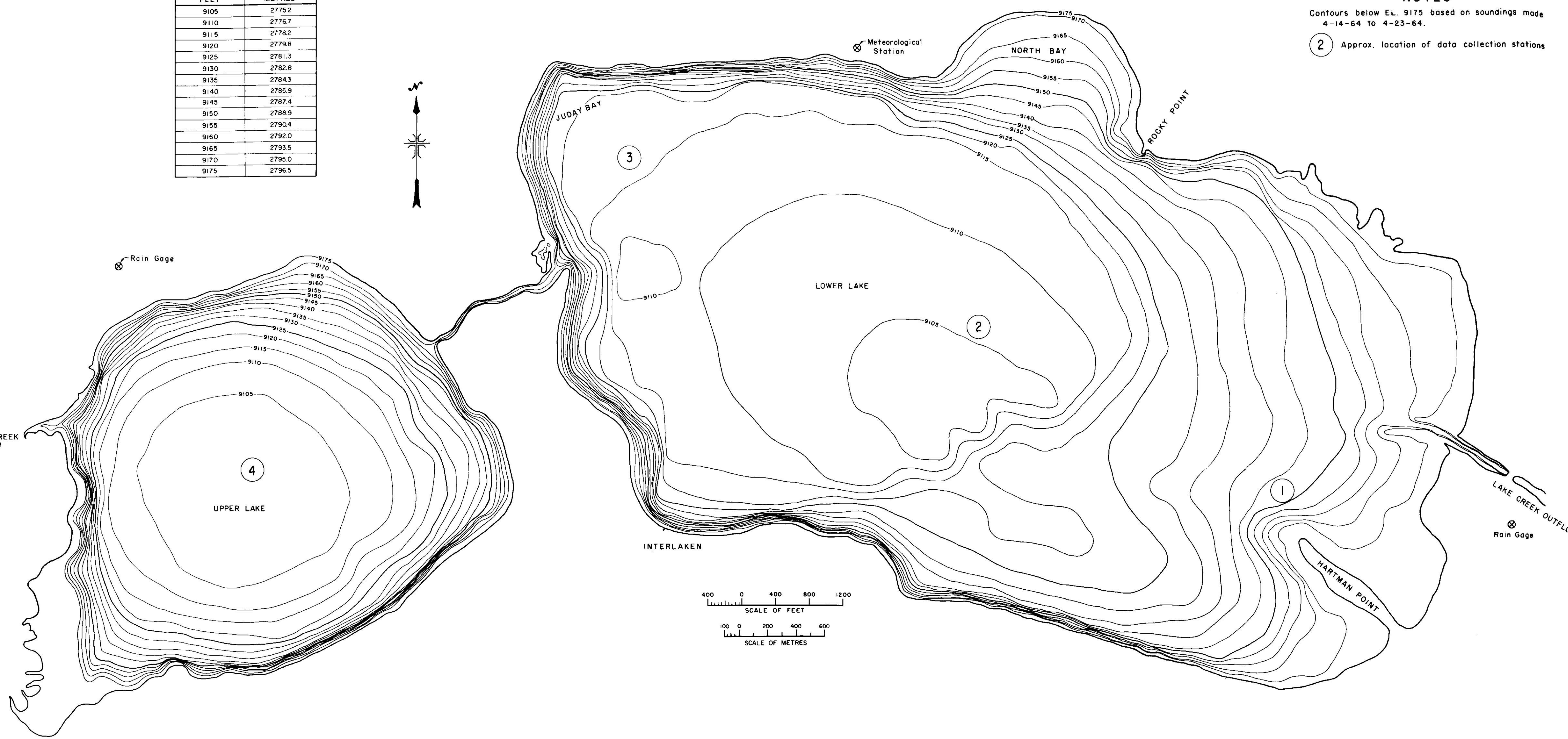


Figure 3.—Bottom topographic map of Twin Lakes.

summarized in table 1. The lower lake is the largest natural mountain lake in the State of Colorado (Pennak [3]).

Table 1.—*Twin Lakes Area-Capacity Data*

Surface elevation, m	Upper lake Area, ha	Upper lake Capacity, m³	Lower lake Area, ha	Lower lake Capacity, m³
2774.0	0	0	0	0
2776.7	70.0	1 078 079	105.6	1 105 216
2779.8	103.6	3 742 439	246.1	6 752 179
2782.8	125.4	7 245 579	328.6	15 584 039
2785.9	143.7	11 355 601	386.1	26 482 012
2788.9	155.4	15 922 018	438.7	39 069 879
2792.0	164.7	20 804 211	476.3	53 018 297
2795.0	174.8	25 975 043	533.0	68 330 966
2798.0	206.4	31 834 168	616.7	85 813 362
2801.1	248.1	38 739 301	710.2	106 039 061
2802.0	263.4	41 078 017	736.5	112 653 088

HISTORICAL BACKGROUND

First mention of Twin Lakes in scientific literature occurs in progress reports of the U.S. Geological and Geographical Survey of the Territories for the years 1873 and 1874 (Hayden [6, 7]). These reports focus on the glacial origin of the lakes and describe them as being much the same in size and shape as they are today. Three physical features which have since disappeared are mentioned: a waterfall on Lake Creek at the point where it emerges from the canyon above Twin Lakes, an extensive marshy meadow on the west shore of the upper lake, and a difference in elevation between the upper and lower lake of approximately 2 m (6.6 ft).

By 1889, when David Starr Jordan visited the area during his seining expedition through Colorado and Utah, the waterfall above the lakes had been destroyed by blasting and placer mining operations had created a turbidity problem in the main stem of the Arkansas River (Jordan [8]). Jordan reported that Twin Lakes contained suckers, minnows, and two species of native trout, one of which, the yellowfin (*Salmo clarki macdonaldi*), was described as a new species indigenous to the lakes (Jordan and Evermann [9]).

The irrigation section of the annual report by the U.S. Geological Survey for 1889-1890 (Powell [10]) contains a rather detailed proposal for converting Twin Lakes into a single storage reservoir. Included in this proposal were a large dam across the valley below the lakes and a canal diverting water from the Upper Arkansas into the new reservoir. Powell noted that the annual fluctuation in the surface elevations of the lake at that time probably did not exceed 0.6 m (2 ft).

Twin Lakes were converted into irrigation storage reservoirs in 1901, when the Twin Lakes Reservoir Company dammed the natural outlet of the lower lake and built a deeper, controlled outlet works that permitted an extreme water level fluctuation of 7.8 m (25.5 ft) in the lower lake and about 5.8 m (19.0 ft) in the upper (Juday [11]).

Chauncey Juday carried out a limnological survey of Twin Lakes for the U.S. Bureau of Fisheries during the summers of 1902 and 1903 (Juday [11, 12]). While no chemical data were reported, his physical observations are generally similar to those of the present study. Juday's biological data, however, indicate that diversity, and perhaps abundance of zooplankton and fish, were greater than in recent years (LaBounty et al. [13]). Four new species of fish, including the Mackinaw trout (*Salvelinus namaycush*), had been introduced since Jordan's 1889 visit, while the yellowfin trout had become extremely rare. Juday wrote that, during late summer, a placer mining diversion frequently dried up Lake Creek above Twin Lakes, stranding large numbers of brook trout and greatly reducing the inflow to the lakes.

Several important changes took place in the 55 years between Juday's work and the next known limnological study at Twin Lakes. The Twin Lakes Tunnel, bringing water from the Roaring Fork drainage under the Continental Divide and into Lake Creek, was completed in 1935 (Ubbelohde et al. [14]). At some point in this interim period, the stream connecting the upper and lower lakes was dredged so that today both lakes fluctuate essentially as one reservoir (Nolting [15]). The swampy meadow west of the upper lake is mentioned for the last time by Juday [11, 12]; today that area is largely a barren flood plain. In 1957, W. D. Klein [16] of the Colorado Department of Game and Fish introduced the *Mysis* shrimp into the lower lake from Clearwater Lake, Minn., on an experimental basis.

D. H. Nolting [15] of the Colorado Department of Game, Fish and Parks, did some limnological work at Twin Lakes between 1958 and 1961 as part of a larger study of the lake (Mackinaw) trout in Colorado. Nolting's physical and chemical data are in general agreement with those reported here, while the biological data indicate that the zooplankton species *Daphnia* and the Colorado speckled dace (*Rhiniehthys*) have either disappeared from the lakes or become extremely rare since his study. He reported that, as of 1968, there was still no indication that Klein's experimental *Mysis relicta* plant had been successful.

L. M. Finnell of the Colorado Division of Wildlife began fishery investigations on the entire Fryingpan-Arkansas Project in 1970. In his first progress report, Finnell [17] reported that the success of the Twin Lakes *Mysis* introduction became evident in 1969 and that shrimp transplants out of the lakes into other lakes and reservoirs began in 1970.

The study reported here began in May 1971 and has been coordinated with the Colorado Division of Wildlife's investigations at Twin Lakes since its inception.

METHODS AND MATERIALS

Field Survey Methods

Nearly 5 years of physical and chemical field data have been collected utilizing a variety of methods and equipment. Table 2 summarizes the physical-chemical field survey methods used in this study from 1971 through 1976. In each column, the various techniques and pieces of equipment are listed starting with the earliest and ending with the most recently used.

Four rafts have been anchored in the lakes as permanent survey stations (fig. 3). Rafts 1 through 3 are located on a southeast to northwest axis across the lower lake, while raft 4 is anchored in the center of the upper lake. At maximum water surface elevations, the sampling ratio in Twin Lakes averages about one station per 254 ha (629 acres) of lake surface. The rafts are replaced with barrel buoys during the winter months, because buoys are less susceptible to ice damage.

Field surveys at Twin Lakes were carried out on an irregular, more or less seasonal basis from August 1971 through April 1974. Since May 1974, surveys have been done on a more regular basis, usually monthly, and at times even biweekly. Winter surveys are accomplished by working through holes bored in the ice at or near the usual sampling stations.

A typical physical-chemical field survey at Twin Lakes consists of the following:

1. Measurement of temperature, D.O. (dissolved oxygen), pH (hydrogen ion concentration), conductivity, and Eh (oxidation-reduction potential)

Table 2.—*Summary of physical-chemical field survey methods,* 1971-76

Water temperature	Dissolved oxygen (D.O.)	Hydrogen ion concentration (pH)	Conductivity	Oxidation-reduction potential (Eh)	Light: Transparency (light penetration)	Light: Transmissivity (turbidity)
Whitney underwater thermometer	Samples and modified Winkler or Hach kit	Samples and Sargent pH probe	Samples and conductance cell with Lab-line Wheatstone bridge		Secchi disk	Samples and colorimeter
Yellow Springs D.O. probe (thermometer)	Yellow Springs D.O. probe				Hydro Products relative irradiance meter	
Hydrolab surveyor (multiparameter probe)	Hydrolab surveyor (multiparameter probe)	Hydrolab surveyor (multiparameter probe)	Hydrolab surveyor (multiparameter probe)	Hydrolab surveyor (multiparameter probe)	Limnophotometer with selenium barrier photo cells	Hydro Products transmissometer

at various depths from surface to lake bottom with the Hydrolab electronic multiparameter probe.

2. Determination of Secchi depth with a standard 200-mm black and white disk; summer only.

3. Collection of two water samples at each of three depths (surface, thermocline or mid-depth, and bottom) with a VanDorn or Kemmerer water sampler for laboratory chemical analyses; the two samples are a 1-l sample for standard water quality analysis and a 0.5-l sample, fixed with 1 ml of nitric acid, for analysis of heavy metal content.

4. Collection of a bottom sediment sample with a Petersen or Ekman dredge for laboratory analysis of heavy metal content.

5. Measurement of the light extinction curve with a selenium barrier photo cell limnophotometer; summer only.

Transmissivity measurements with a Hydro Products transmissometer were added to the regular survey on a few occasions during the summer. Water samples for water quality and heavy metal analyses were also collected from the Lake Creek inflow and outlet of the lakes.

Field Instrumentation

The four rafts which serve as permanent survey stations were also used to support data recording systems and transducers for measuring water surface temperature, air temperature, and windspeed. Air temperature and windspeed were measured at a height of 2 m (6.5 ft) above the water surface. The raft instrumentation is shown on figure 4.

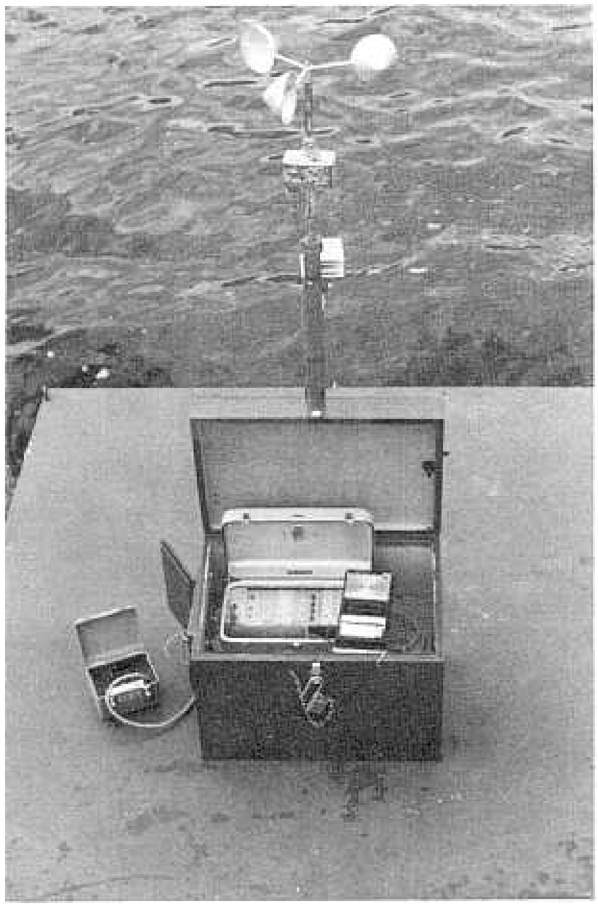


Figure 4.—Raft weather data recording system with anemometer and air temperature sensor.

Thermographs were installed at the U.S. Forest Service gaging station on Lake Creek above Twin Lakes and just below the outlet works of the lower lake for recording inflow and outflow temperatures. A recording rain gage was installed on the north shore of the upper lake and another southeast of the lower lake outlet (fig. 3). Stage gages for measuring water surface elevation were established on both the upper and lower lakes. A meteorological station, consisting of a small trailer housing a data acquisition system and a mast carrying wind and radiation instruments (fig. 5), was established at the site of the lower lake stage gage (fig. 3).

Block diagrams on figures 6, 7, and 8 show the relationship of the various components of each instrumentation system. Table 3 references each component numbered on the block diagrams with information on its source and use.

Careful consideration was given to the design of the field instrumentation to minimize the number of analog recorders and to record as many parameters as possible in digital format. Reduction of analog data into a format for machine processing is time consuming, while digital data are usually in a format easily entered into a computer system.

The inflow-outflow water temperature recorders, two rain gages, and upper lake stage gage were analog instruments chosen because others were either prohibitive in price or lacked a suitable power source. The meteorological station system and the four raft systems, which were used to collect the bulk of the data, were digital instruments and recorded these data on magnetic tape. Except for windspeed and direction, the measurements were made with analog transducers.

Figure 5.—Twin Lakes meteorological station.

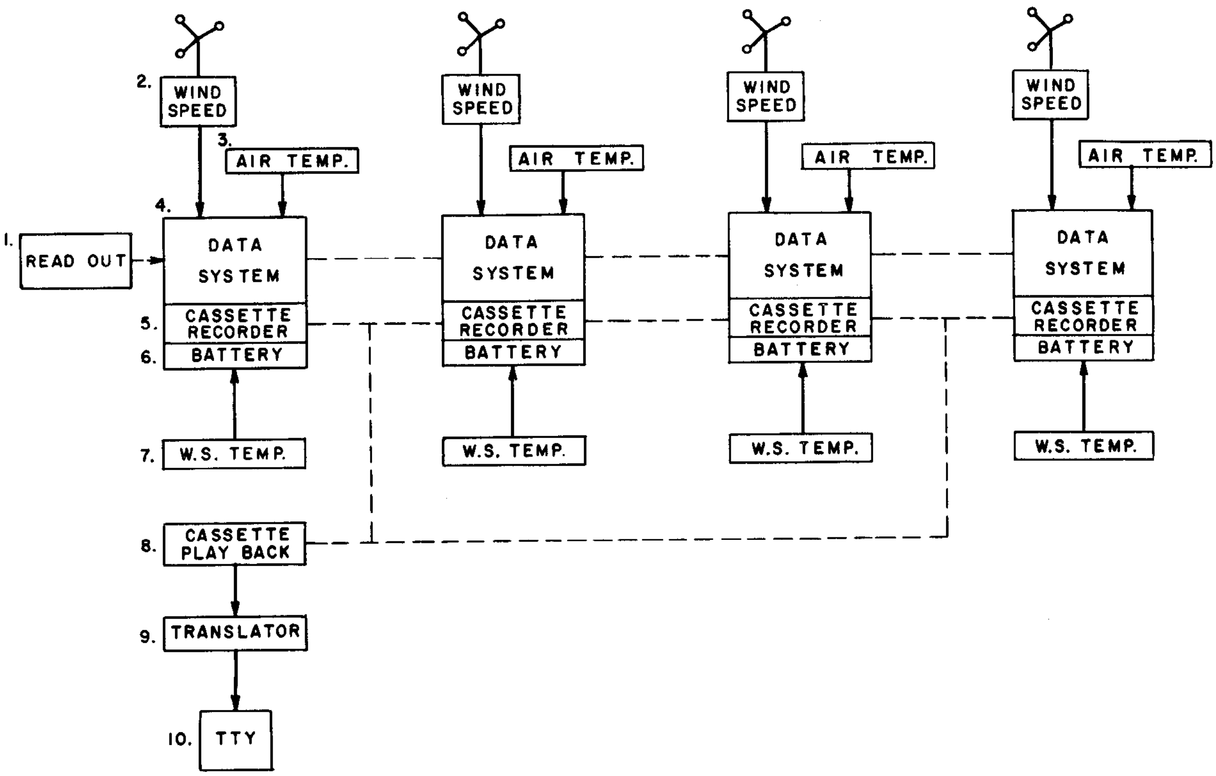


Figure 6.—Raft weather instrumentation diagram.

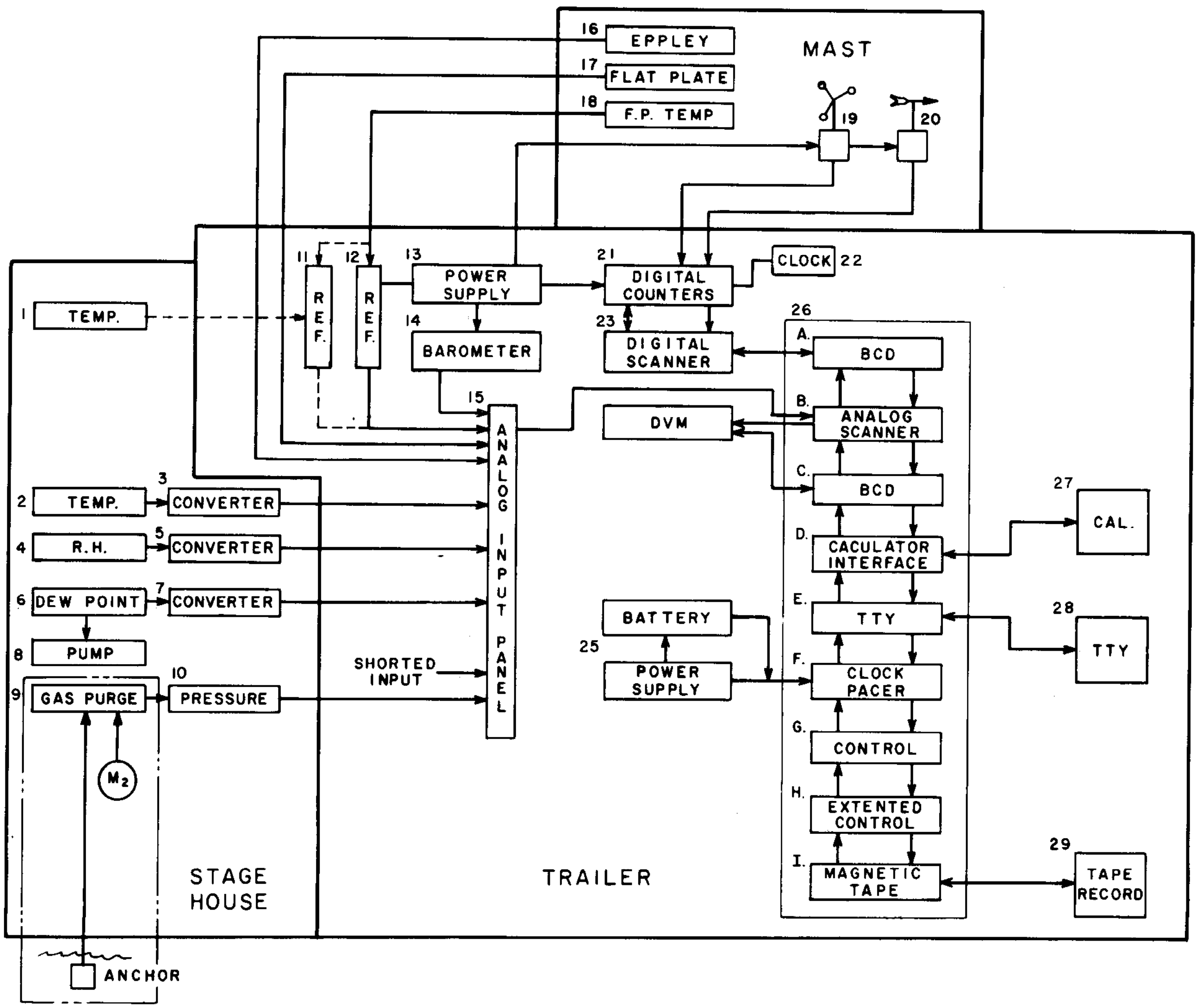


Figure 7.—Meteorological station instrumentation diagram.

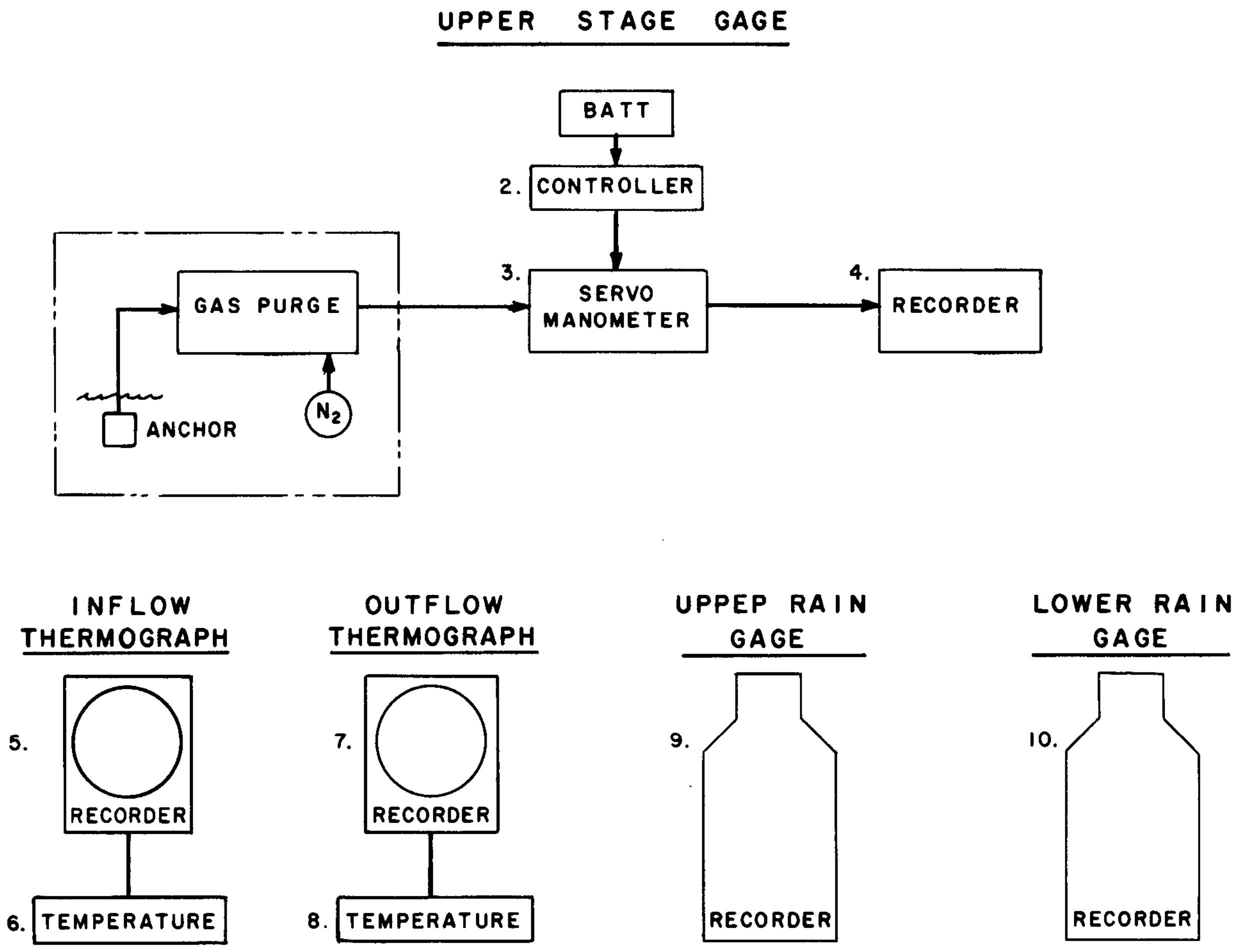


Figure 8.—Upper stage gage, thermograph, and rain gage instrumentation diagrams.

Table 3.—*Instrumentation summary*

No.	Component	Source	Use
		RAFTS	
1	Readout	Ball Brothers Research Corporation	On-the-spot readout of data
2	Anemometer	Belfort Instrument Company	2-m windspeed
3	Linear thermistor	Yellow Springs Instrument Company, Inc.	2-m air temperature
4	Data system	Ball Brothers Research Corporation	A/D, time, input-output
5	Cassette recorder	Panasonic-Matsushita Electric Corporation	Digital data recorder
6	Gel battery	Various sources	System power
7	Linear thermistor	Yellow Springs Instrument Company, Inc.	Water surface temperature
8	Cassette playback	Panasonic-Matsushita Electric Corporation	Playback of recorded data
9	Translator	Ball Brothers Research Corporation	Converts FSK to ASCII
10	Teletype	Teletype Corporation	Paper tape for computer
		METEOROLOGICAL STATION	
1	Thermocouple	Bureau of Reclamation	Corrects R. H. transducer (4)
2	Linear thermistor	Yellow Springs Instrument Company, Inc.	As 1 above, used in 1974
3	Converter	Bureau of Reclamation	Resistance to voltage conversion
4	LiCl transducer	Hygrodynamics, Inc.	Relative humidity
5	Converter	Hygrodynamics, Inc.	Resistance to voltage conversion
6	Dew point cell	EG&G Cambridge Systems, Inc.	Dew point temperature
7	Converter	EG&G Cambridge Systems, Inc.	Resistance to voltage conversion
8	Vacuum pump	Neptune Corporation	Air sample for dew point
9	Gas purge system	U.S. Geological Survey	Pressure output for stage
10	Pressure transducer	Robinson-Halpern Company	Pressure to voltage conversion
11	Reference	Thermo-Electric Company, Inc.	Ice point reference for thermocouple
12	Reference	Bureau of Reclamation	As 11 above, used in 1974
13	Power supply	Bureau of Reclamation	Provides 5- and 12-volt d.c.
14	Barometer	Weather Measure Corporation	Barometric pressure
15	Input panel	Bureau of Reclamation	Organizes analog inputs and 120-V a-c power
16	Pyronometer	The Eppley Laboratory, Inc.	Solar radiation
17	Flat plate radiometer	Beckman and Whitley, Inc.	Total incoming radiation
18	Flat plate temperature	Integral with No. 17	Back radiation from flat plate
19	Anemometer	Belfort Instrument Company	Windspeed
20	Wind vane	Bureau of Reclamation	Wind direction
21	Digital counters	Bureau of Reclamation	Converts windspeed and direction into digital information
22	Clock	Bureau of Reclamation	Clocks wind direction time
23	Digital scanner	Hewlett-Packard Company	Multiplexes digital counters
24	Digital voltmeter	Hewlett-Packard Company	Analog/Digital converter
25	Power supply	Bureau of Reclamation	Uninterruptible supply to clock
26	Coupler-controller	Hewlett-Packard Company	Organizes and controls input-output
27	Calculator	Hewlett-Packard Company	For power failure and program control
28	Terminal	Texas Instruments, Inc.	Output monitor and cassette tape recorder for data - 1974
29	Tape recorder	Kennedy Company	Data recorder - 1973

Table 3.— *Instrumentation summary (continued)*

No.	Component	Source	Use
		UPPER STAGE GAGE AND OTHER INSTRUMENTS	
1	Gas purge system	U.S. Geological Survey	Pressure output for lake stage
2	Controller	U.S. Geological Survey	Time delay and motor controller for 3
3	Servomanometer	U.S. Geological Survey	Changes pressure to rotary motion
4	Recorder	Leupold and Stevens Instrument, Inc.	Analog recording of stage
5	Recorder	Honeywell, Inc.	Inflow temperature to upper lake
6	Transducer	Part of No. 5	Mercury in steel temperature sensor
7	Recorder	Honeywell, Inc.	Outflow temperature of lower lake
8	Transducer	Part of No. 7	Mercury in steel temperature sensor
9	Rain gage and recorder	Bendix Corporation	Collect and record rainfall
10	Rain gage and recorder	Bendix Corporation	Collect and record rainfall

Data recording and reduction were performed to obtain hourly values of all parameters with the exception of inflow and outflow water temperatures and rainfall. The raft data were recorded at hourly intervals. The air and water surface temperature represent an instantaneous value recorded on the hour while the windspeed was integrated to give an average hourly value.

Radiation data from the type of instruments used in this study require frequent sampling to obtain an accurate integrated value over an hour or longer time period. Radiation values can change rapidly on cloudy days as clouds move over the sensors. In 1973, data were recorded at the meteorological station at 5-min intervals for this reason.

A large amount of data was collected which became difficult to reduce. In 1974, a calculator was added to the system not only to solve frequent power interruption problems, but also to reduce data volume. The sensors were sampled at 1-min intervals and readings were stored in the calculator. These values were used to calculate an average which was then recorded hourly. The volume of data was reduced by a factor of 12, resulting in better data handling efficiency as well as obtaining a better integrated value of each parameter. The digital wind instruments were self-integrating and required sampling only at hourly intervals.

The instrumentation systems were serviced at 1- or 2-week intervals. Tapes and charts were changed; each component was checked for proper operation, and calibrations were made where necessary. Such infrequent field checks are not recommended if reliable data must be obtained 100 percent of the time. Most data losses occurred at the meteorological station from power service interruptions and electronic component failures in the more complex instruments. The raft instrument systems, except for early component failures, proved to be extremely reliable and could be left unattended for periods greater than a month, depending on the recording capacity of the cassette tapes.

The field instrumentation was, in part, innovative at the time it was first installed, using state-of-the-art techniques and components. While this instrumentation is far from obsolete, anyone contemplating similar field measurements would do well to look at the newer electronic technology that has developed rapidly since 1972.

Laboratory Analyses

Chemical examination of water samples was carried out by means of procedures described in APHA (American Public Health Association) Standard Methods [18]. The following is a summary of methods:

1. Specific conductance — conductance cell and Wheatstone bridge
2. TDS (total dissolved solids) — filter through a 0.45-μm filter and evaporate at 105 °C

3. Calcium and magnesium — EDTA (ethylenediamine tetra acetate) titrimetric methods
4. Sodium and potassium — flame photometric method
5. pH and alkalinity — potentiometric titration
6. Sulfate — gravimetric method
7. Chloride — argentometric method
8. Heavy metals — Perkin-Elmer Model 370, atomic absorption spectrophotometer with a heated graphite furnace Model 2100, and a deuterium continuum source

Operating conditions for the heated graphite furnace were as follows:

Element	Approximate sample size, μl	Purge	Atomization temperature, °C
cadmium	50	N_2	1800
lead	50	N_2	2000
manganese	50	N_2	2400
iron	50	N_2	2500
zinc	20	N_2	2100
copper	20	N_2	2500

Detection limits for the above metals have declined over the period of the study. At the time of this report they were as follows:

Element	Detection limit, mg/l
cadmium	0.0001
lead	0.002
manganese	0.005
iron	0.010
zinc	0.002
copper	0.002

Samples of lake bottom sediment arrived in the laboratory in plastic bags. The samples were then air dried and screened through a 1.65-mm screen. Twenty grams were dissolved in 25 percent nitric acid and analyzed for heavy metal content using a Perkin-Elmer Model 303 atomic absorption spectrophotometer.

All heavy metal analytical results reported are in terms of total metal content; that is, dissolved and suspended fractions have not been separated. Attempts to obtain an estimate of the dissolved fraction by analyzing filtered water samples have met with little success.

Golterman [19] and Davies and Goettl [20] have noted that the most reliable method now available for determining the dissolved, or ionic, concentration of metals in water is differential pulse anodic stripping voltammetry. This method was not available for the present study.

METEOROLOGY

Data were collected from the meteorological station only in the summer field seasons of 1973 and 1974. In 1973, data were collected from July 14 through September 25 and in 1974 from June 29 through September 25. Rainfall and lake stage data were collected during the same time period in 1973 and over a somewhat longer period in 1974.

Levels were run to establish that the water surface elevation of both lakes was the same. They differ only at elevations much lower than those encountered during the two data collection seasons. The gentle slope of the lake bottoms in the areas of the gages prevented placing the bubbler tubes in deeper water. At times of decreasing water level, one or the other of these tubes was out of the water or equipment failures occurred and data were lost. However, because the water surface of the lakes was at the same elevation and redundant gages were established, one or the other gage was working at all times and overall, no stage data were lost.

The daily average water surface elevations are shown on figures 9 and 10 for 1973 and 1974. The water surface elevations were nearly the same in July, but considerably more drawdown occurred by the end of September in 1974 than in 1973.

The rain gages on the upper and lower lakes were approximately 4.8 km (3 mi) apart. A comparison of the daily rainfall (figs. 11 and 12 for 1973 and figs. 13 and 14 for 1974) shows the very localized effects of shower activity and the differences that can occur in short distances both in amounts of rainfall and time of occurrence. As an example, the upper lake on July 12 through July 15, 1973, received a total of 13 mm (0.52 in) and the lower lake 25 mm (0.99 in) on July 12 through July 14 with no rainfall on July 15. Similar occurrences are found throughout the season in both years. This spatial and time variation points to the importance of rain gage networks when working with precise energy or water budgets.

It should be noted that the lower rain gage was in operation through the month of October in 1973 and 1974, while data for the upper gage are shown only through September 25 in 1973 and October 28 in 1974.

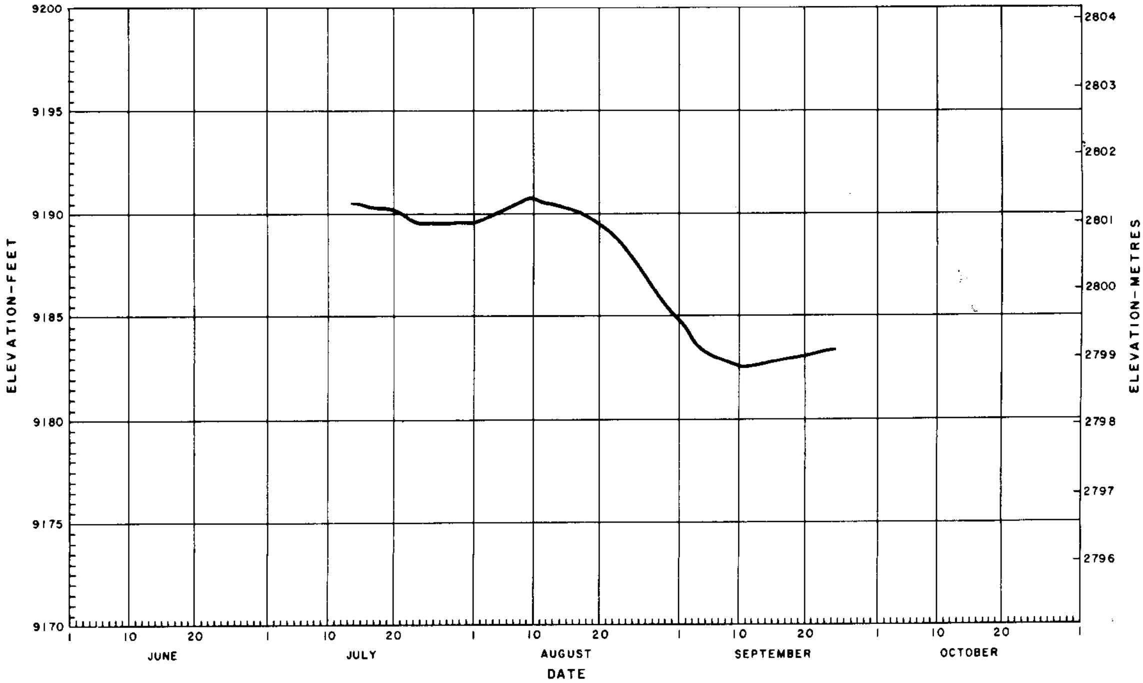


Figure 9.—Daily average water surface elevation — 1973.

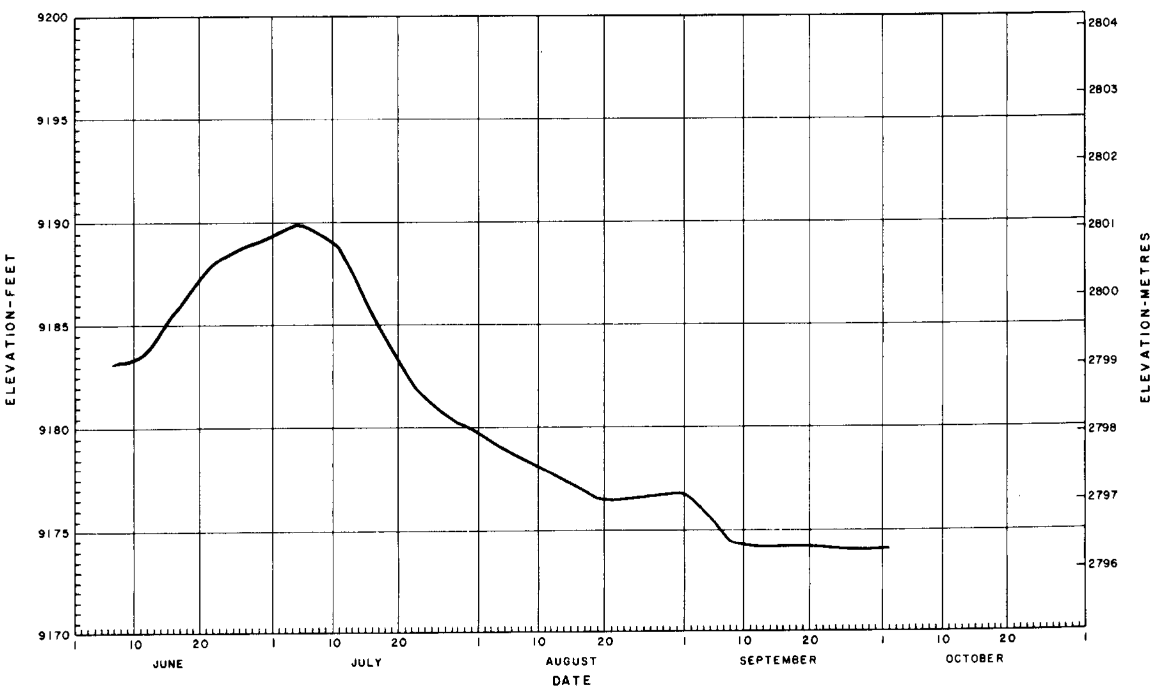


Figure 10.—Daily average water surface elevation — 1974.

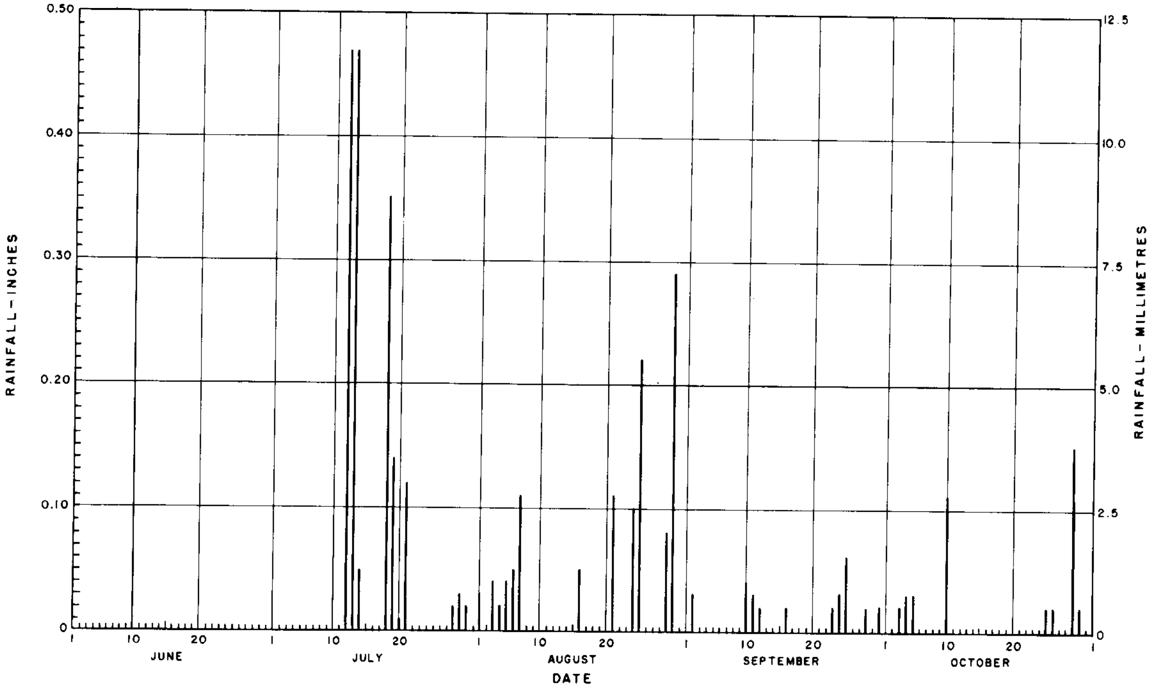


Figure 11.—Daily rainfall, lower lake station — 1973.

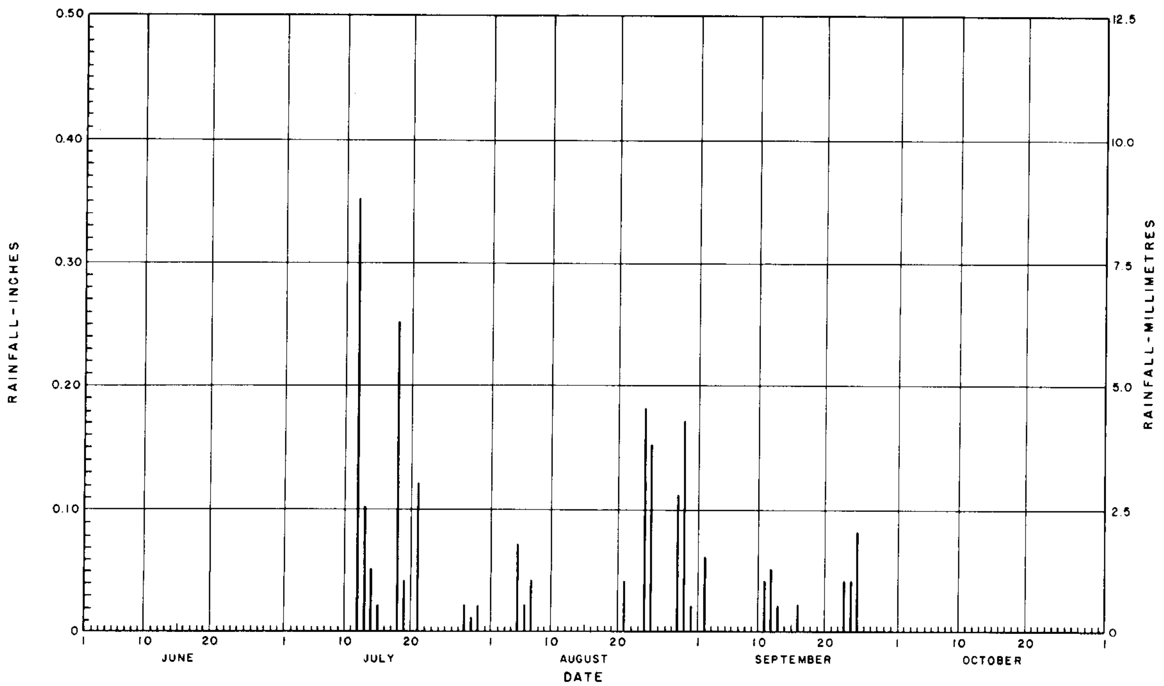


Figure 12.—Daily rainfall, upper lake station — 1973.

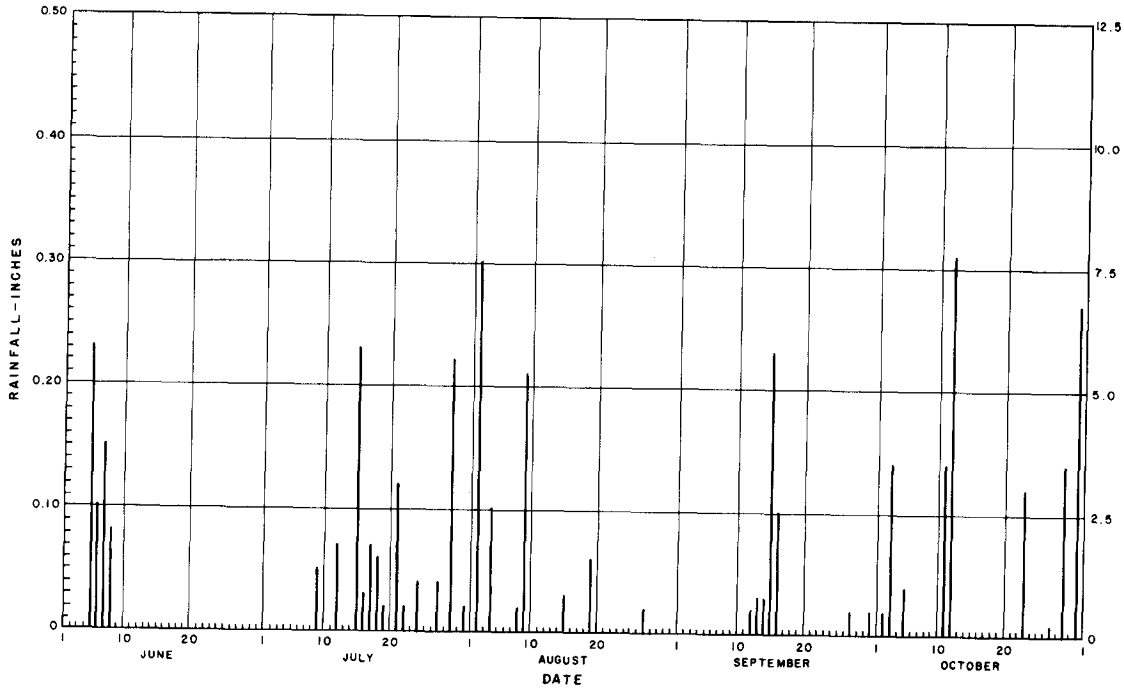


Figure 13.—Daily rainfall, lower lake station — 1974.

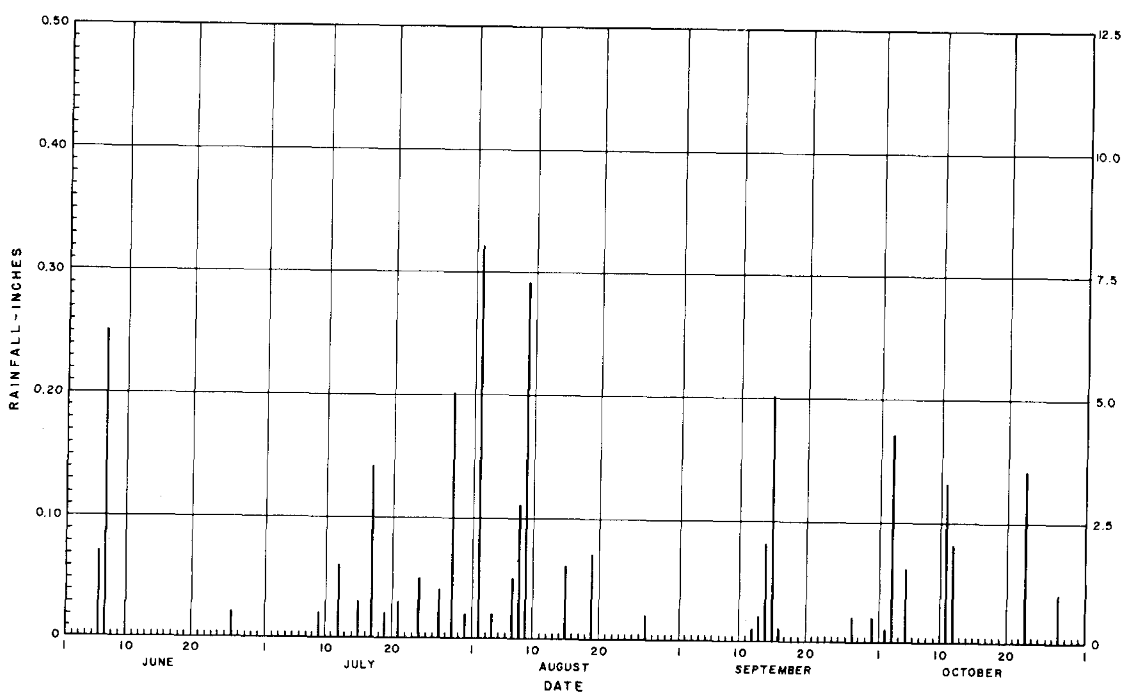


Figure 14.—Daily rainfall, upper lake station — 1974.

The daily total incoming radiation for the 1973 and 1974 seasons is plotted on figures 15 and 16. The daily total solar radiation measured with the Eppley Pyrheliometer for the same time period is plotted on figures 17 and 18. The 1974 radiation values were slightly higher than those in 1973. The daily averages for both seasons were approximately 4644.24×10^4 J/m^2 (1110 langleys) for the total incoming radiation and 1966.48×10^4 J/m^2 (470 langleys) for the solar radiation.

Data losses are apparent from an examination of the plotted data, in particular from August 4 through August 15, 1973 and from August 30 through September 16, 1974. The losses occurring in 1973 resulted from a power failure and are indicated by a straight line which is the average of data several days before and after the period lost. In 1974, the data loss resulted from an electronic failure. Although radiation tends to balance around an average over short portions of a year, this period of missing data was considered too large to estimate.

The daily averages for the dew point temperature, relative humidity, and barometric pressure are shown on the series of figures 19 through 24. Vapor pressure of the air can be computed from either dew point or relative humidity and air temperature. Previous efforts in making reliable long-term humidity measurements in the field have proven difficult. The lithium-chloride transducer used for measuring the relative humidity has been used extensively by the USBR in the past. This transducer, which is actually a series of sensors, each measuring a narrow range, is subject to calibration changes through contamination and aging. The dew point sensor uses a thermoelectric-cooled mirror maintained at the dew point by optically sensing a thin layer of dew on the mirror. The mirror temperature, or dew point, is measured with a temperature sensor in contact with the mirror.

The hourly dew point temperature values were converted to relative humidity and compared to the measured relative values. The measured values were generally lower but varied by different amounts, depending on the relative humidity value. A calibration shift can occur in some of the individual sensors of the lithium-chloride transducer without greatly affecting measurements in other ranges. Periodic calibration comparisons with a battery-operated psychrometer showed a larger variation in the lithium-chloride transducer system than in the dew point system. The relative humidity values should, therefore, be used only for trends and not absolute values.

Wind direction patterns for the two seasons can be compared on figures 25 and 26. There was an almost even distribution of wind from all directions except the south, southwest, and west. The western direction indicates a predominately downslope wind from the alinement of the Lake Creek Valley. The southerly wind diversion is probably an influence of the higher mountains just to the south of Twin Lakes on the downslope winds. The reason for the shift in the predominate southerly wind in 1973 to a predominately southwesterly wind in 1974 is not readily apparent from an examination of the data. In 1974, wind measurements were started earlier in the season and higher daily averages were recorded in September of that year.

HYDROLOGY

Twin Lakes receive almost the entire runoff of the Lake Creek drainage basin, plus flows diverted from the Roaring Fork River through the Twin Lakes Tunnel under the Continental Divide (fig. 27). Nearly all this water enters the lakes via Lake Creek, the principal tributary and sole outlet.

The Lake Creek drainage basin covers an area of approximately 238 km^2 (92 mi^2). Altitudes within this watershed range from 4399 m (14 433 ft) above mean sea level at the summit of Mt. Elbert to about 2758 m (9050 ft) at the confluence of Lake Creek and the Arkansas River.

Daily discharge measurements of Lake Creek above and below Twin Lakes (i.e., at the inlet and outlet of the lakes) are plotted on figure 28 for the period from October 1971 through September 1975. These data were provided by Mr. G. E. Brees of the office of the Colorado State Water Resources Engineer. The annual pattern of these flows is well illustrated by the mean discharge plots on figure 29.

May through August is the main runoff period for Lake Creek with maximum annual flows usually occurring in June. Mean maximum flow during 1971-75 was about 32.5 m^3/s (1150 ft^3/s), while winter flows averaged about 0.3 m^3/s (10 ft^3/s).

Outflow from Twin Lakes follows irrigation demand in the Lower Arkansas River Valley, so that the general pattern is one of high flows from April into early September. Average flow during the irrigation period was about 11.0 m^3/s (390 ft^3/s) in 1971-75. Winter outflows are usually quite small and in most years, the gaging station is closed for the winter. During the

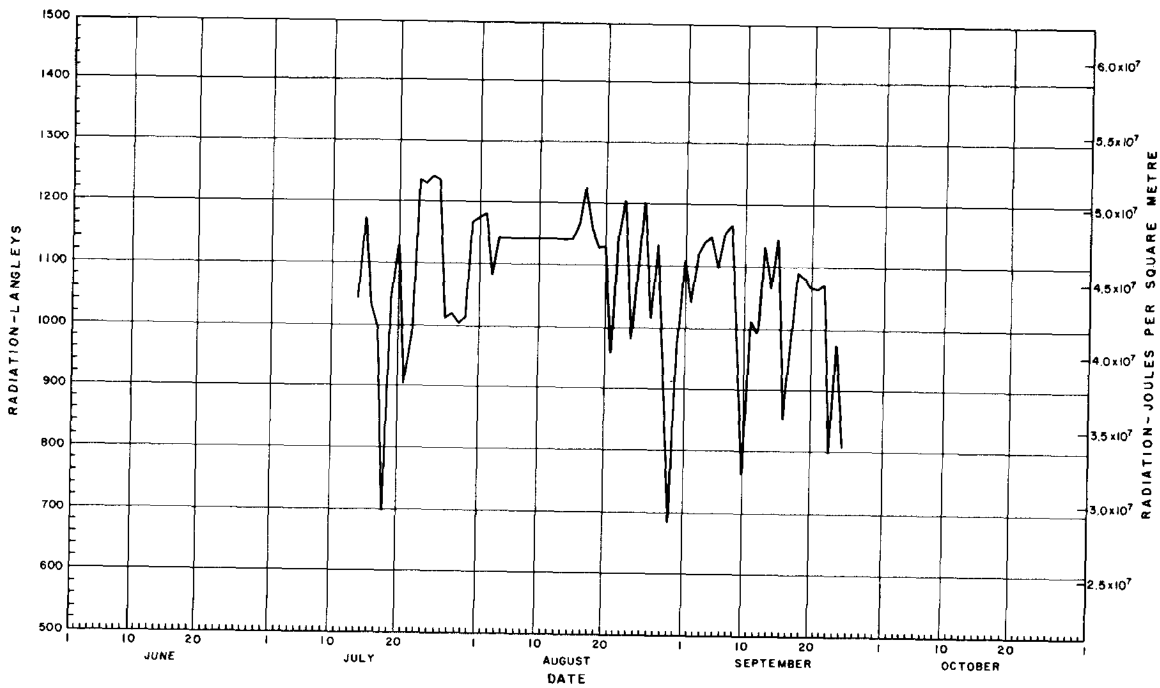


Figure 15.—Daily total incoming radiation — 1973.

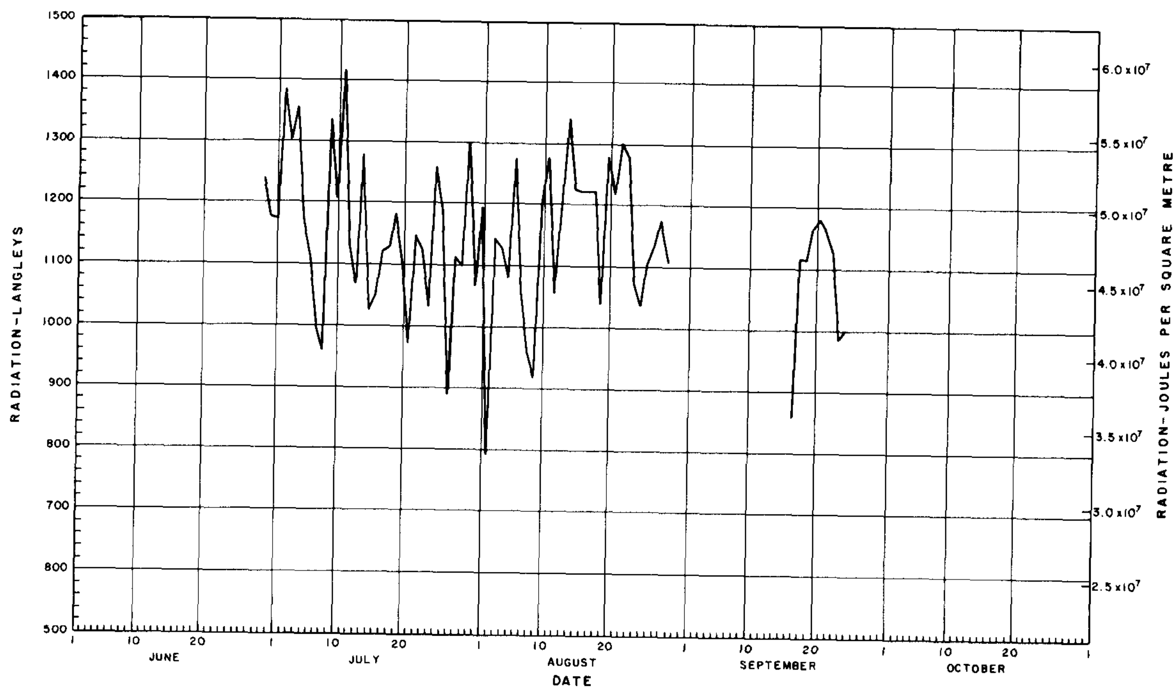


Figure 16.—Daily total incoming radiation — 1974.

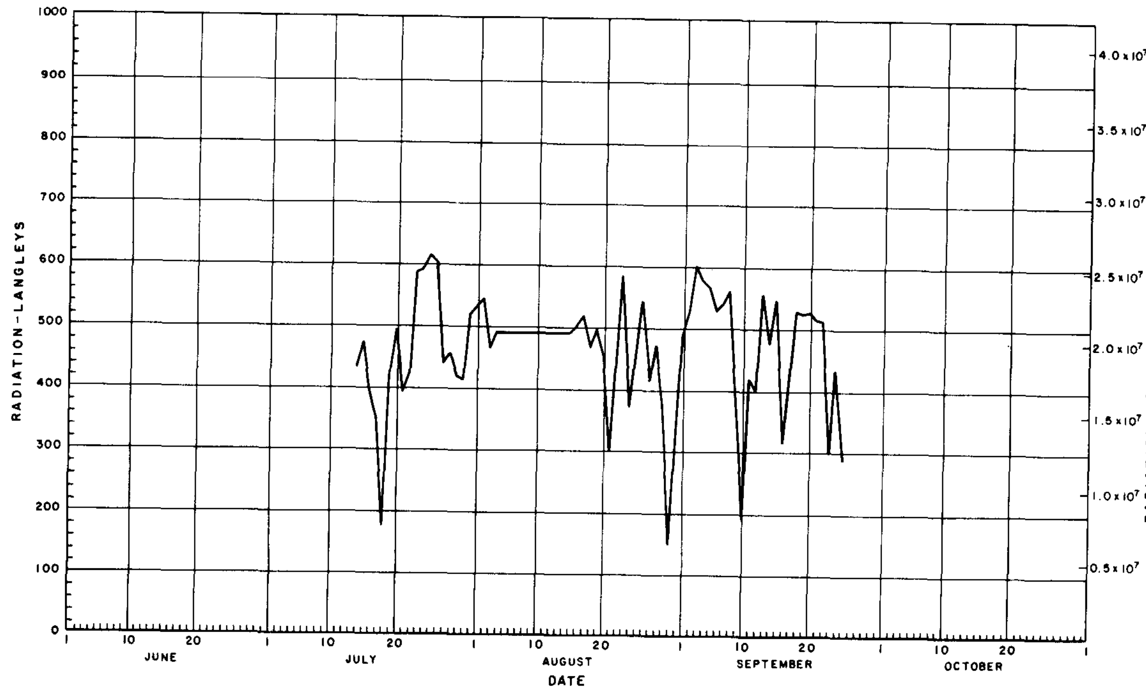


Figure 17.—Daily total solar radiation — 1973.

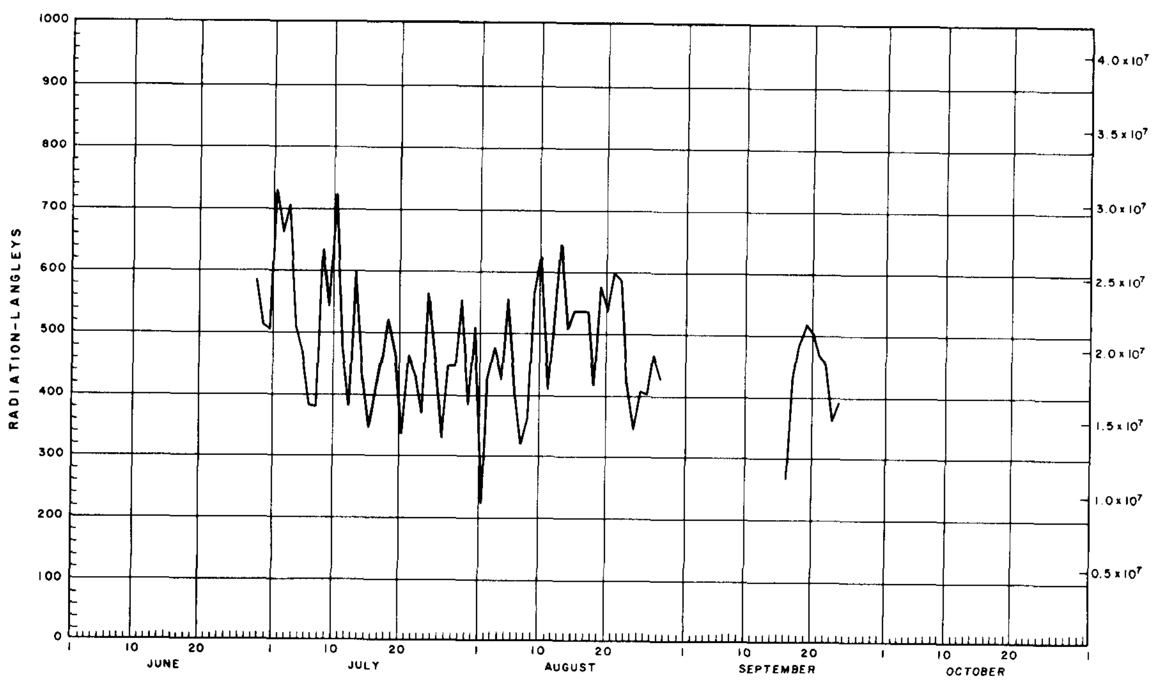


Figure 18.—Daily total solar radiation — 1974.

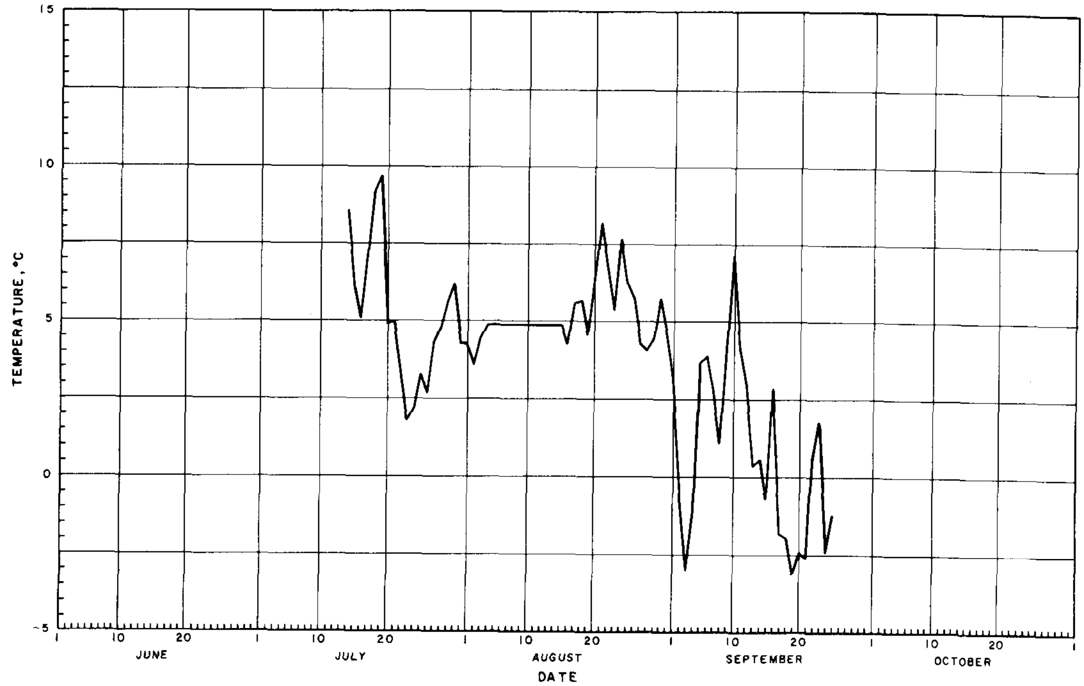


Figure 19.—Daily average dew point — 1973.

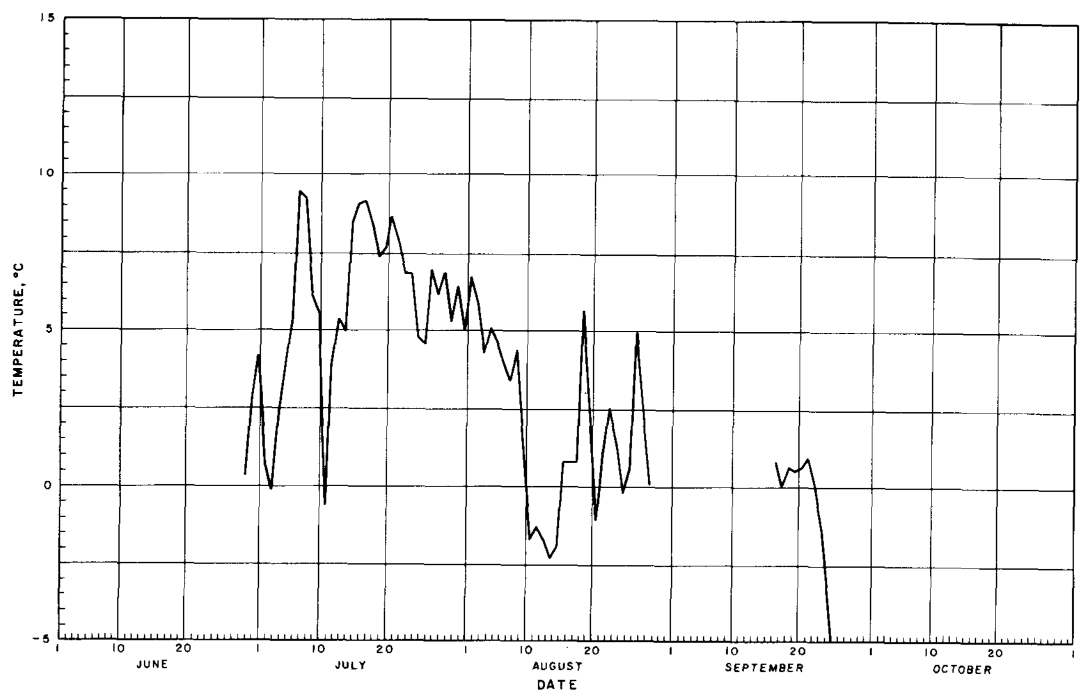


Figure 20.—Daily average dew point — 1974.

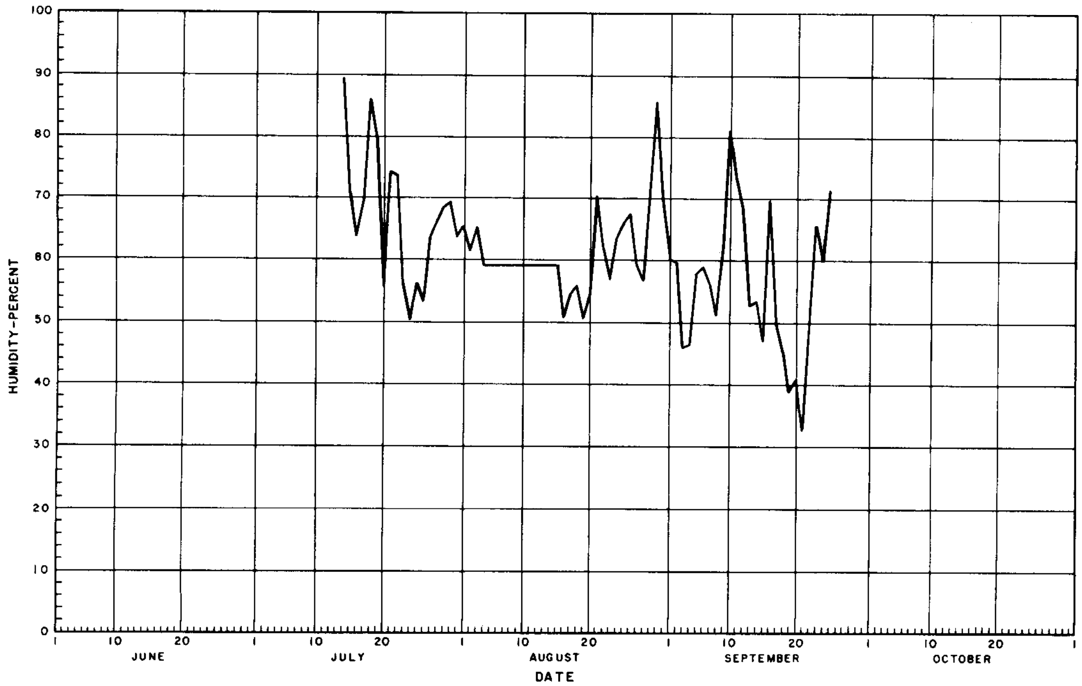


Figure 21.—Daily average relative humidity — 1973.

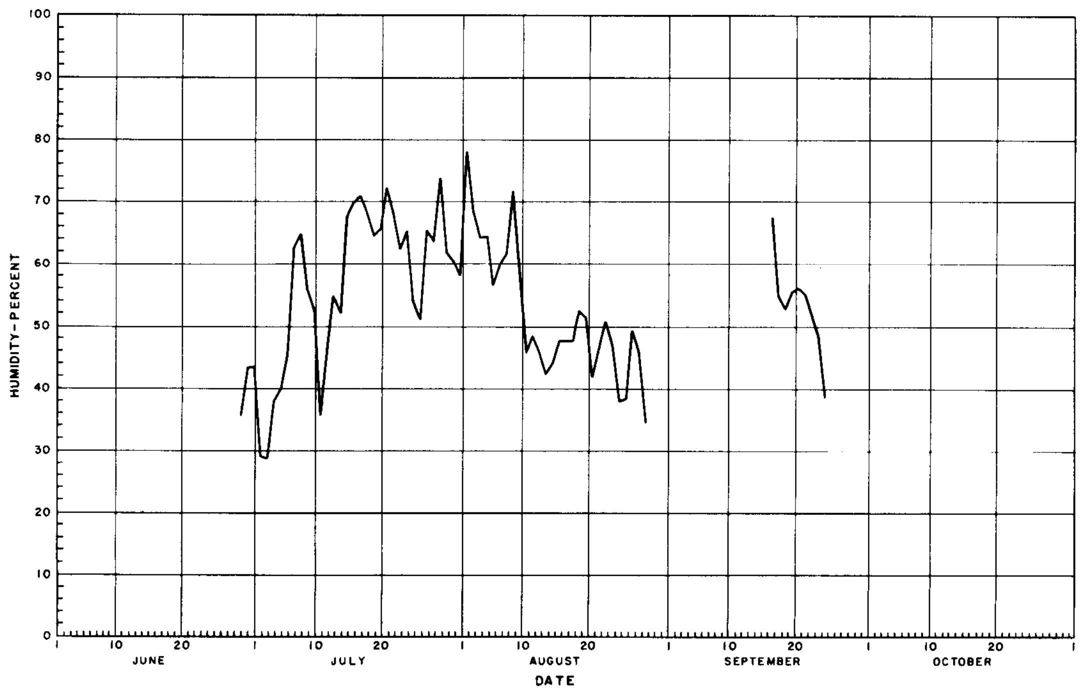


Figure 22.—Daily average relative humidity — 1974.

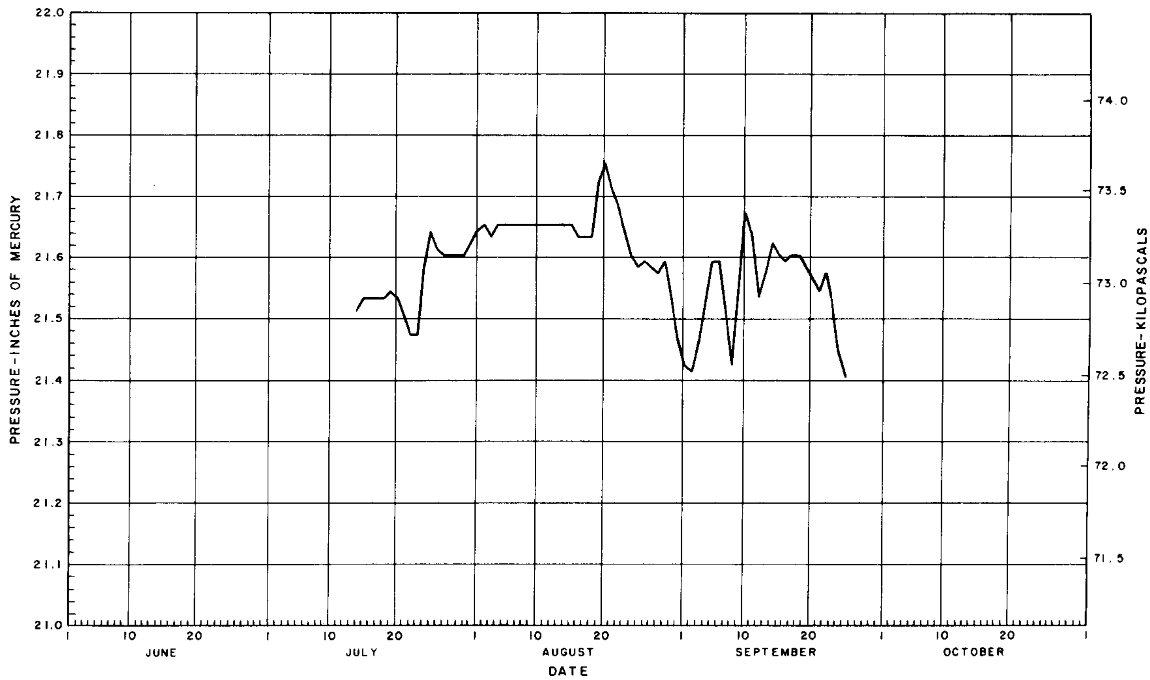


Figure 23.—Daily average barometric pressure — 1973.

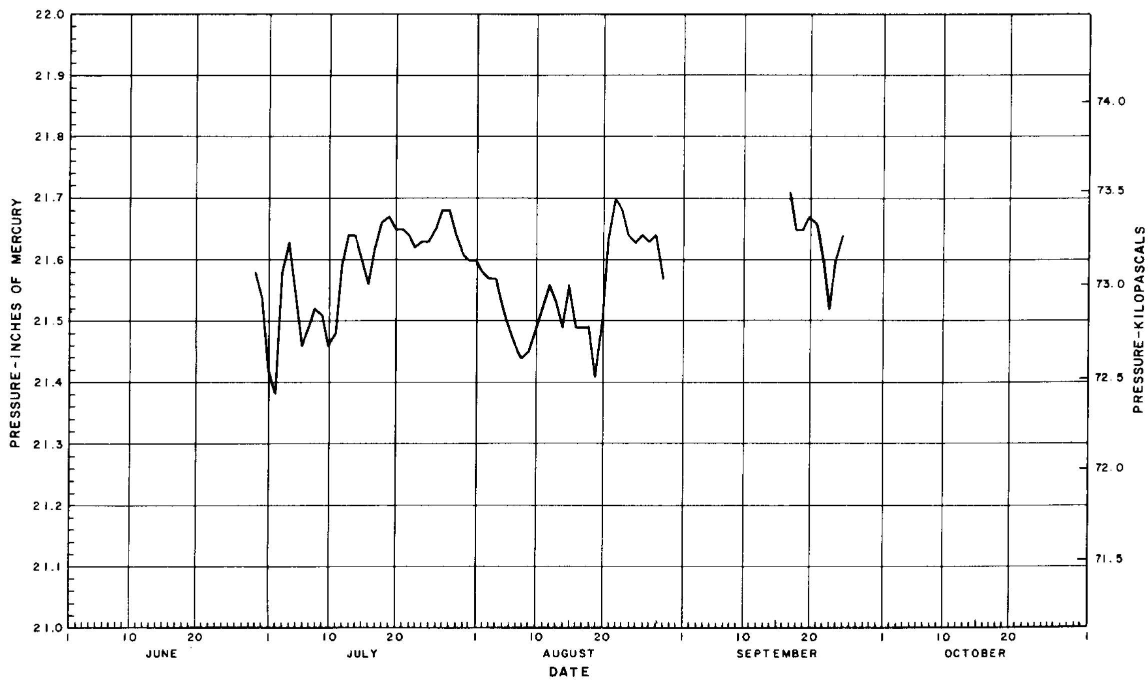
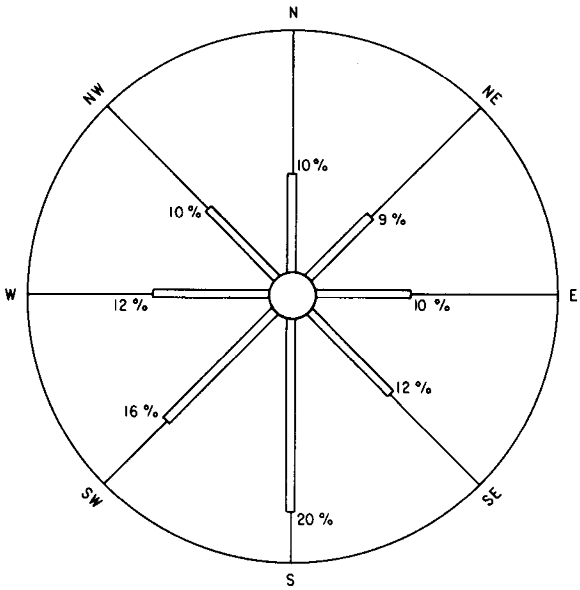
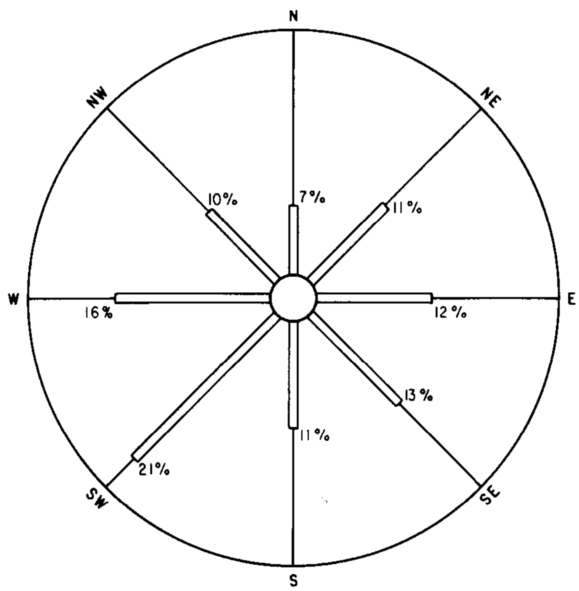


Figure 24.—Daily average barometric pressure — 1974.



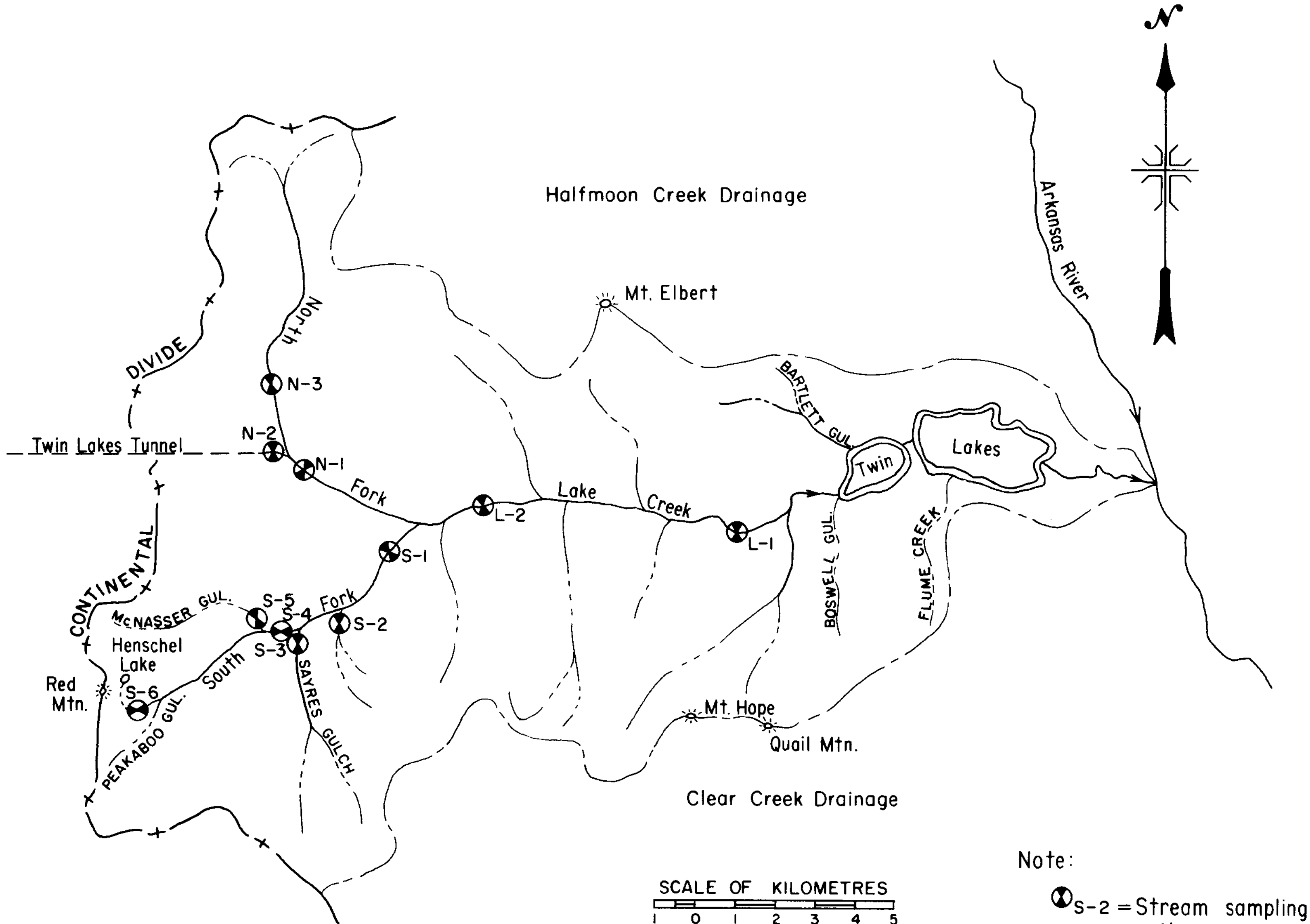
PER CENT OF WIND FROM INDICATED DIRECTION

Figure 25.—Wind direction pattern — 1973 season.



PER CENT OF WIND FROM INDICATED DIRECTION

Figure 26.—Wind direction pattern — 1974 season.



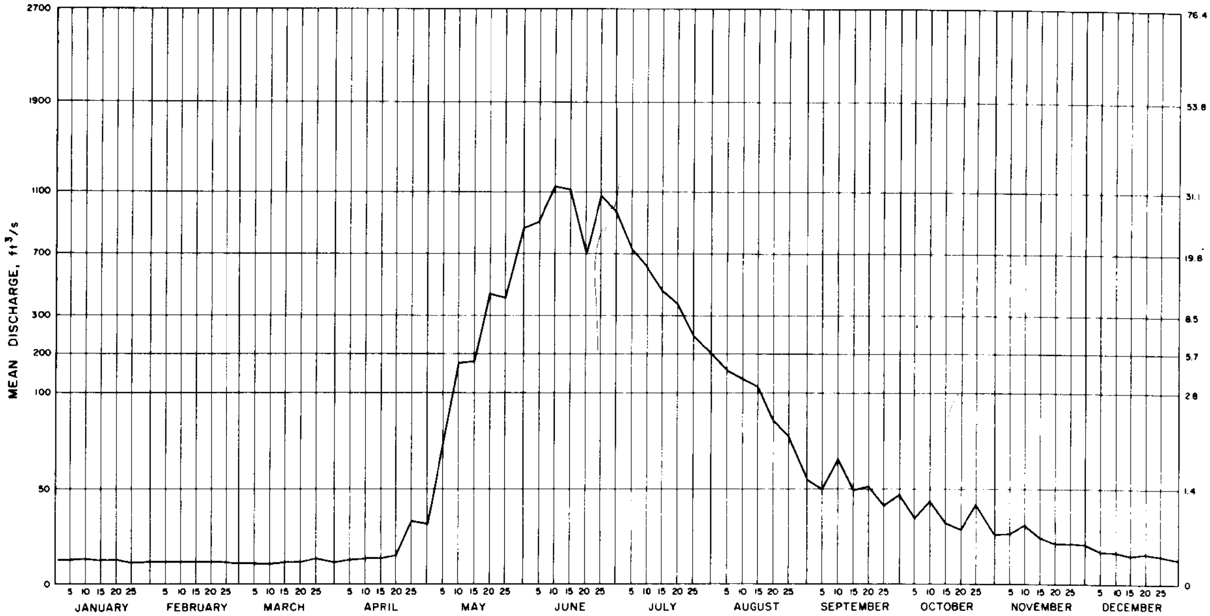
(Adapted from U.S.F.S. map of San Isabel Nat'l Forest, Colo.)

Figure 27.—Map of Lake Creek drainage, Colo.

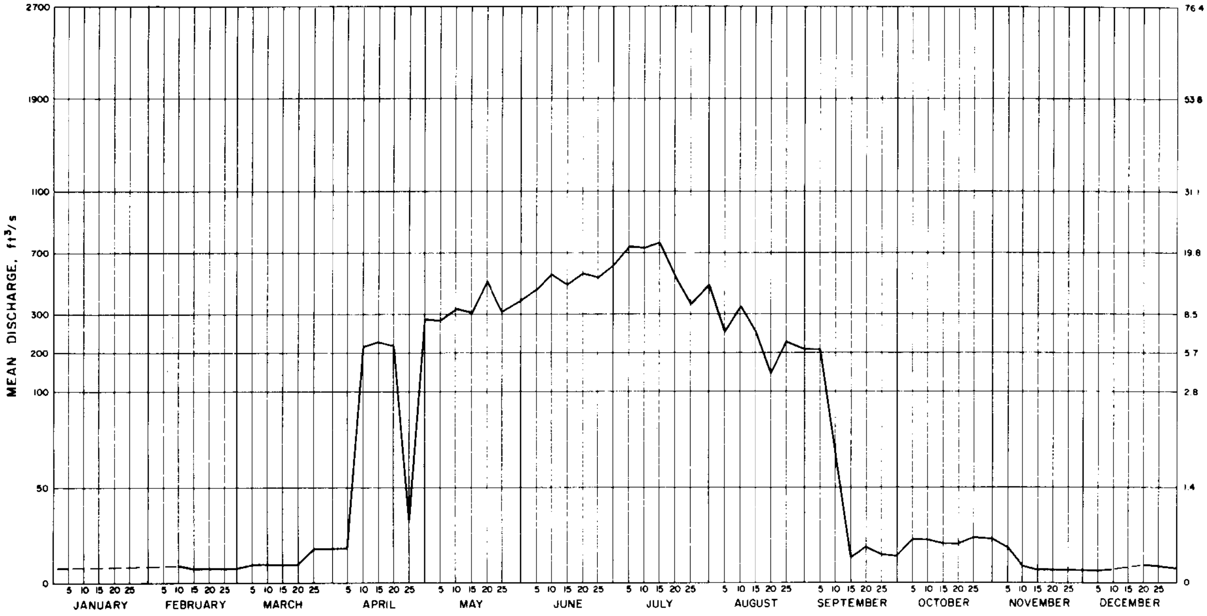
(a) ABOVE TWIN LAKES (i.e., TWIN LAKES INFLOW)

(b) BELOW TWIN LAKES (i.e., TWIN LAKES OUTFLOW)

Figure 28.—Lake Creek discharge, 1971-1975.



(a.) ABOVE TWIN LAKES (i.e., TWIN LAKES INFLOW)



(b.) BELOW TWIN LAKES (i.e., TWIN LAKES OUTFLOW)

Figure 29.—Mean Lake Creek discharge, 1971-1975.

winter of 1973-74, however, significant releases were made from Twin Lakes during December and January (fig. 28) to make up flows from Turquoise Reservoir which could not be delivered to the lower valley because of ice conditions in the Arkansas above Lake Creek.

Average total annual runoff for the period from October 1971 through September 1975 was 154.365 x 10^6 m^3 (125 145 acre-ft). This volume of runoff is large in relation to the total capacity of the lakes (table 1). For example, the ratio of the total capacity of Twin Lakes to the average total annual runoff in Lake Creek is 1.0. Corresponding ratios for the upper and lower lakes are 0.3 and 0.7, respectively. These relationships are reflected in the estimated flushing times for the lakes (fig. 30). At maximum lake elevation (2802 m above mean sea level) and the 1971-75 mean inflow rate of about 4.9 m^3/s (173 ft^3/s), flushing times for the lakes would be about 3 months for the upper and 9 months for the lower.

These figures are somewhat misleading, however, because flows in Lake Creek are distributed in a highly uneven fashion. A peak June inflow of 32.5 m^3/s, for example, would flush the upper lake in 15 days or less and the lower lake in no more than 40 days. Typical winter flows of about 0.3 m^3/s, on the other hand, would take at least 2½ years to flush the upper lake and more than 6 years for the lower.

As will be seen below, the wide variation in inflow rate has a particularly strong effect on chemical and physical conditions in the upper lake because of its smaller volume in relation to the total volume of inflow, and the fact that it receives the full impact of Lake Creek, serving as a holding pond or settling basin in relation to the lower lake.

LIGHT

The optical properties of Twin Lakes were studied under two general headings: transparency and transmissivity. Transparency refers to the penetration and absorption of sunlight in the lake water column, while transmissivity is a measure of turbidity at given depths within the lake.

Transparency

As sunlight passes from the surface downward into a body of water, it is reduced in intensity according to the following equation (Clarke [21]):

$$\theta = \theta_0 e^{-\eta z} \qquad (1)$$

where:

θ = light intensity at any depth, z

θ_0 = original light intensity at zero depth (i.e., after surface losses)

η = light extinction (or absorption) coefficient

z = depth

It may be seen from equation (1) that the extinction coefficient, η, is an index of the transparency of the water body. As the value of η decreases, the depth to which a given intensity of sunlight penetrates increases. Extinction coefficients, determined from photometer measurements at Twin Lakes from 1972 through 1975, are listed in table 4.

A biologically more relevant index of transparency is the euphotic depth, Z_{ED}. Euphotic depth is defined as that depth at which the light intensity is 1.0 percent of the original, zero-depth light intensity (Cole [22]). Cole comments that, "Below this somewhat arbitrary depth, primary productivity is usually considered nil." Monthly values of Z_{ED}, determined from the 1974 and 1975 extinction coefficients (table 4), are plotted on figure 31.

Another, rather more subjective index of transparency, is the Secchi depth, Z_{SD}. [Secchi depth is the depth at which a 200-mm (8-in) diameter white disk disappears from view when lowered into a body of water.] Secchi depths determined during the 1974 and 1975 ice-free seasons are also plotted on figure 31.

Distinct upper and lower lake transparency trends are evident in the data presented on figure 31. In general, the upper lake exhibits a trend from low June transparencies to relatively clear conditions in October and November. The lower lake, on the other hand, exhibits a more nearly level trend with less variation about the seasonal mean. Both lakes underwent a more extreme variation in transparency in 1975 than in 1974. This variation was mainly due to extremely low transparencies in June and July 1975. A comparison of figure 31 with figure 28, in the Hydrology section of this report, shows that these reduced transparency conditions coincided with a later and larger runoff in 1975 compared to 1974.

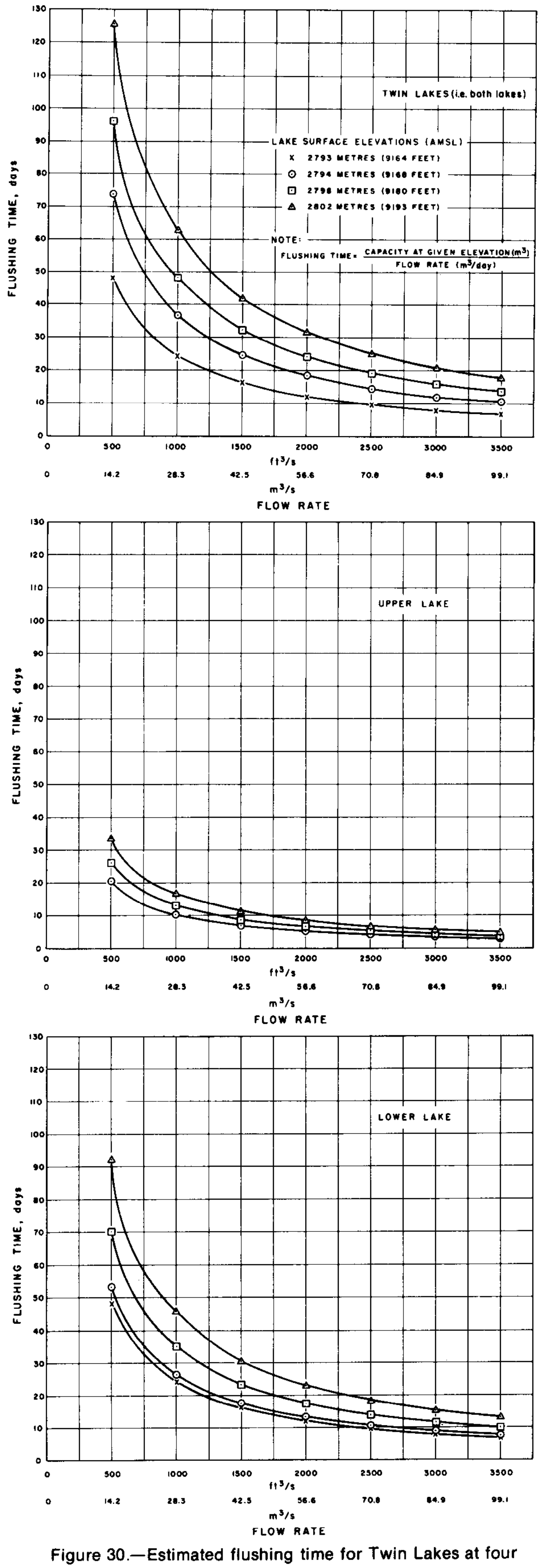


Figure 30.—Estimated flushing time for Twin Lakes at four water surface elevations.

Table 4.—*Light extinction coefficients*

Year	June	July	Aug.	Sept.	Oct.	Nov.
	Months					
			*η			
upper lake						
1973	—	—	0.85	—	—	—
1974	0.74	0.54	0.56	0.53	0.47	0.41
1975	1.38	1.28	0.49	0.42	0.35	0.41
Mean	1.06	0.91	0.63	0.48	0.41	0.41
lower lake						
1972	—	—	—	0.62	—	—
1973	—	—	0.51	—	—	—
1974	0.46	0.40	0.44	0.39	0.42	0.47
1975	0.53	0.73	0.43	0.39	0.42	0.47
Mean	0.51	0.56	0.47	0.47	0.42	0.47

*η = light extinction coefficient in m^{-1}

Figure 32, showing average Secchi and euphotic depths for the period 1972 through 1975, confirms the general trends noted on figure 31. Upper lake transparency, as reflected by mean extinction coefficient (table 4), is strongly correlated with the Lake Creek inflow rate ($r = 0.99$). Lower lake extinction coefficients, however, are relatively more independent of the inflow rate ($r = 0.77$). Mean value of the light extinction coefficient for the upper lake for the period 1972-1975 was 0.63 m^{-1} (0.19 ft^{-1}) and for the lower lake 0.47 m^{-1} (0.14 ft^{-1}). Note, however, that late-season transparencies in both lakes trend toward approximately the same levels. Apparently the upper lake functions as a settling basin between the turbid spring inflows of Lake Creek and the relatively clear lower lake.

Juday [11] made the following observation on the transparency of Twin Lakes during the summers of 1902 and 1903: "It was found that, in general, a Secchi's disk just disappeared from view at a depth of about 5.5 m (18 ft) early in July, and the water gradually became more transparent as the season advanced, so that, by the middle of August, this depth had increased to a maximum of 9 m (29.5 ft)." Although Juday did not specify to which lake these Secchi depths applied, they may be compared to the mean 1972-1975 July and August Secchi depths:

	July	August
Upper Lake	1.9 m (6.2 ft)	4.1 m (13.4 ft)
Lower Lake	4.6 m (15.1 ft)	4.2 m (13.8 ft)

The maximum Secchi depth recorded during this period was a single 9-m (29.5-ft) determination in the upper lake in September 1975.

Table 5 compares the mean light extinction coefficients of Upper and Lower Twin Lakes with those of 16 other lakes cited in the literature. Within this representative group, Twin Lakes rank as being relatively clear.

Two lakes listed in table 5, Trout Lake and Crystal Lake in Wisconsin, were mentioned in two or more references. In each of these cases, the earlier references consistently show the lake to be clearer than the more recent references. This historic decrease in clarity is probably the result of increasing eutrophication. Similarly, the decrease in recorded Secchi depths in the interval between Juday's study and the present investigations at Twin Lakes is probably at least partially caused by eutrophication (Bergersen [26]). Increased flows in Lake Creek since the completion of the transmountain diversion in 1935 are another probable factor contributing to the decline in transparency, especially in the upper lake.

In summary, then, Twin Lakes are relatively clear compared to other lakes mentioned in the limnological literature, but their transparency has declined significantly since Juday's study in 1902-1903.

Transmissivity

Hutchinson [5] notes that there is more vertical variation in the clarity of a lake than would appear from transparency measurements which relate vertical illumination to depth. The transparency measurements discussed above tend to integrate any variations with depth into a smooth curve of light extinction for the entire column of water, equation (1). Details lost in this integration, however, could yield valuable information on such factors as current patterns and plankton distribution within a lake. To recover this detail, transmissometers, consisting essentially of a light source and a photometer attached to opposite ends of a rigid rod and lowered horizontally into a lake, are used to measure the transmissivity of the water at given depths. Transmissivity is an index of the clarity of water at a particular depth and is defined by the following expression:

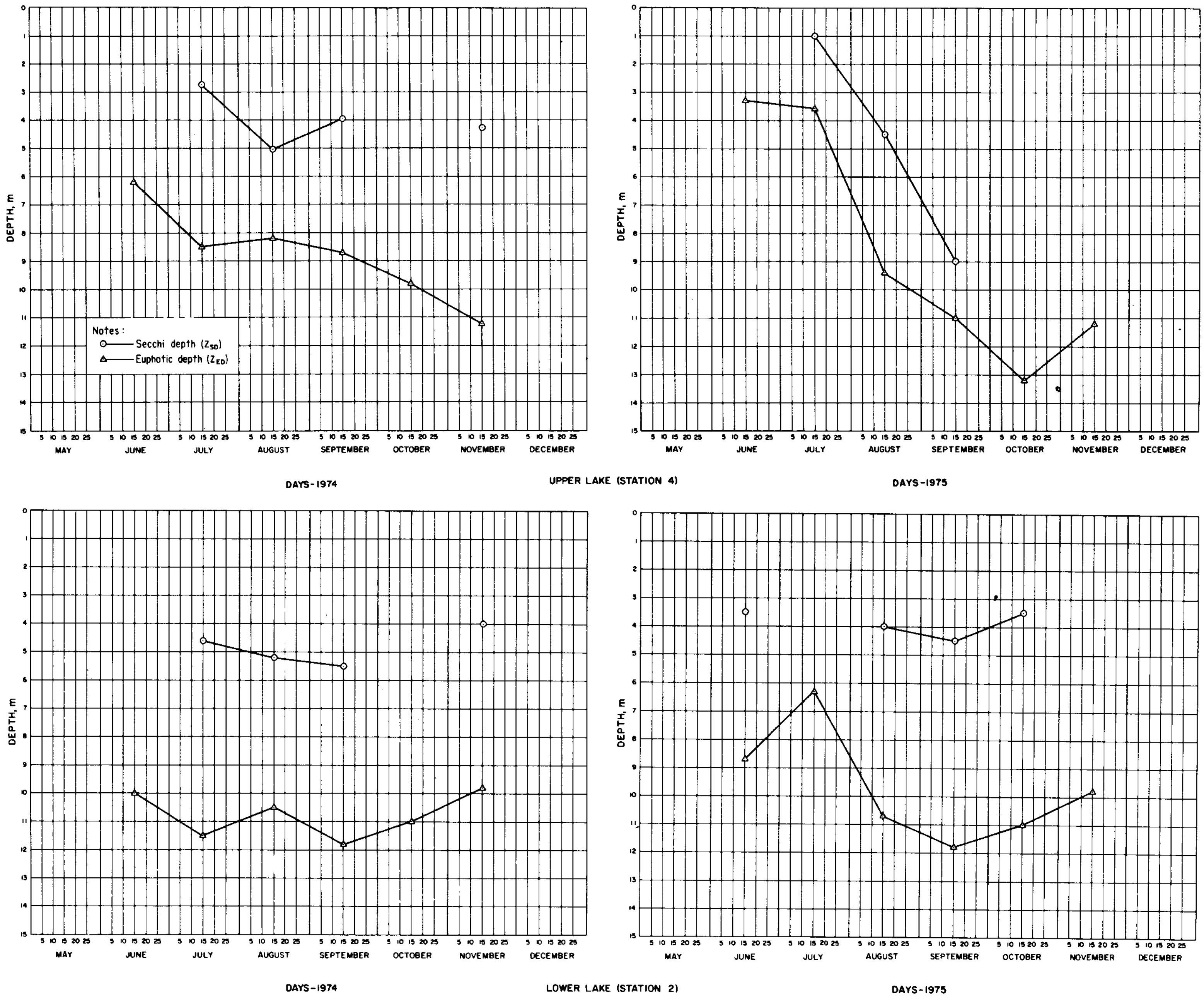
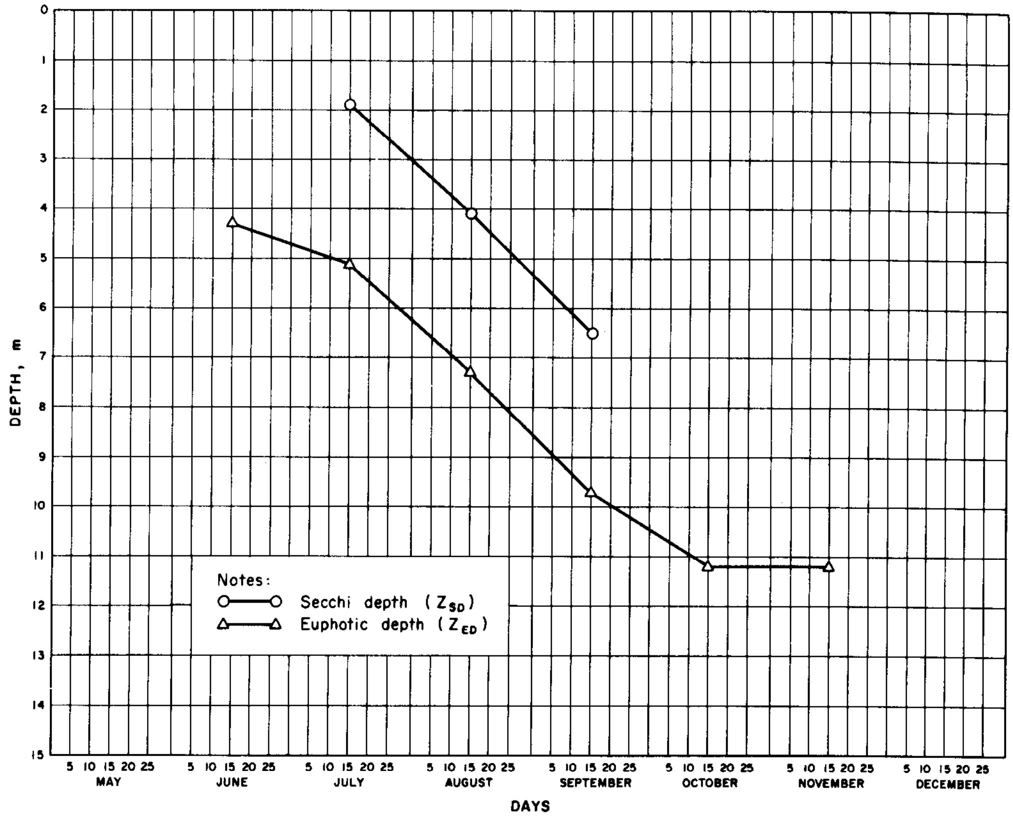
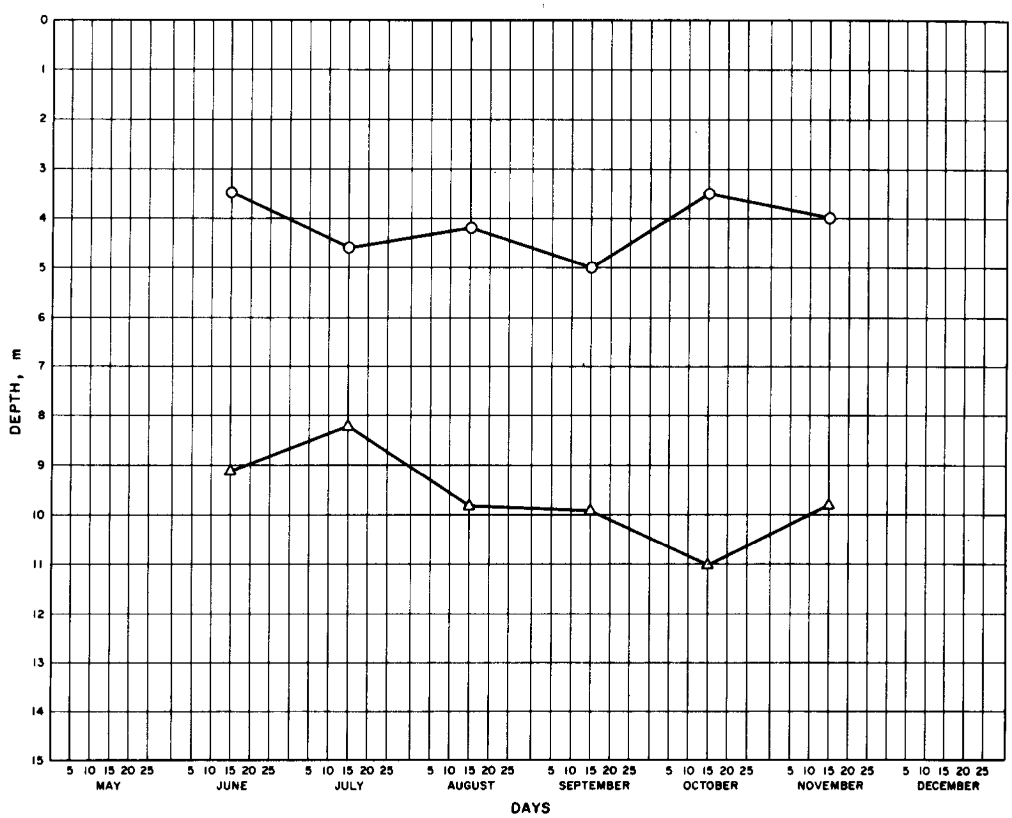


Figure 31.—Light penetration in Twin Lakes, 1974-1975.



UPPER LAKE (STATION 4)



LOWER LAKE (STATION 2)

Figure 32.—Light penetration in Twin Lakes, 1972-1975 averages.

$$T = \frac{I_p}{I_s}(100) \quad (2)$$

where:

T = transmissivity, in percent

I_p = light intensity detected by the photometer

I_s = light intensity transmitted by the light source

Data on horizontal light transmission at various depths in Twin Lakes are limited to three observations in each lake in 1973 (fig. 33) and two in each lake in 1975 (fig. 34). Temperature profiles, Secchi and euphotic depths, zooplankton counts, chlorophyll *a* measurements, and Lake Creek inflow temperatures in the upper lake have been included on figures 33 and 34, when available, to facilitate interpretation of the transmissivity data.

Table 5.—*Comparison of light extinction coefficients*

Lake	$\eta(m^{-1})$	Reference*
Little Triste, Ariz.	12.9	1
Itasca, Minn.	4.3	1
Little Star, Wis.	3.9	2
Saguaro, Ariz.	3.3	1
Montezuma Well, Ariz.	2.3	1
Seneca, N.Y.	1.6	1
Trout, Wis.	1.7	3
Trout, Wis.	0.375	2
Little John, Wis.	0.994	2
Mud, Wis.	0.944	2
Seminoe, Wyo.	0.93	4
Mendota, Wis.	0.88	3
Long, Minn.	0.83	1
Ruth, Wis.	0.81	2
Allequash, Wis.	0.714	2
Crystal, Wis.	1.2	1
Crystal, Wis.	0.27	3
Crystal, Wis.	0.192	2
Muskellunge, Wis.	0.30	2
Tahoe, Calif.-Nev.	0.28	1
Twin Lakes, Colo.		
Upper	0.63	(1972-1975 mean)
Lower	0.47	(1972-1975 mean)

*1. Adapted from Cole [22]
2. Whitney [23]
3. Ryan and Harleman [24]
4. LaBounty et al. [25]

Ruttner and Sauberer (from Hutchinson [5] found an inverse correlation between transmissivity and total plankton numbers in their 1938 study of Austrian lakes. Based upon his studies of several Wisconsin lakes, Whitney [27, 28] described the following generalized pattern of transmissivity with depth:

- Transmissivity was essentially constant in a well-marked, freely circulating epilimnion.

- A marked minimum in transmissivity usually occurred just below the epilimnion and was often accompanied by an increase in particulate organic matter.

- Elaborate microstratification existed throughout the hypolimnion with a sudden drop in transmissivity usually occurring near the bottom. There was some evidence that this hypolimnetic pattern depended on the bacterial population.

Whitney [28] also noted large populations of *Daphnia* in the area of minimum transmissivity just below the epilimnion. In one lake, however, a transmissivity maximum occurred at this depth, apparently as a result of heavy grazing of the phytoplankton by *Daphnia pulex*.

The transmissivity data from Twin Lakes presented on figures 33 and 34 appear to conform generally with the patterns noted in references [27] and [28]. Although plankton data are not available for comparison with the 1973 transmissivities (fig. 33), the marked minima indicated in the thermocline region in both lakes on June 28 are suggestive of Whitney's observations in Wisconsin. A more complete comparison is possible for the 1975 transmissivities (fig. 34). While Twin Lakes, particularly the upper lake, are relatively low in biological productivity (LaBounty et al. [13]), plankton populations do appear to have a definite effect on the August transmissivities in both lakes. There is even a suggestion of the clearing effect of zooplankton grazing, mentioned by Whitney, in the transmissivity profile of August 13 at station 2. The marked hypolimnetic transmissivity minimum at station 4 on June 10, however, is probably explained by the cold, turbid inflow of Lake Creek rather than by any bacterial action.

In general, the limited transmissivity data available for Twin Lakes seem to indicate a progressive clearing of the water at all depths throughout the summer as turbidity, brought into suspension by the spring turnover and runoff, settles. Transmissivity in both lakes seems relatively independent of depth except in the region of the thermocline, where plankton populations are concentrated, and at the bottom of the upper lake during spring runoff, when the colder, sediment-laden water of Lake Creek plunges to the bottom.

TEMPERATURE

An impoundment's temperature structure (i.e., the variation of water temperature with depth) is the end result of interactions among several physical factors, including weather, hydrology, morphometry, and water transparency.

Temperature structure is thus the definitive component of the physical limnology of a lake and the framework for chemical and biological aspects of the lake ecosystem.

Local weather conditions and hydrology of Twin Lakes have been discussed in previous sections. Their effect on the temperature structure of the lakes is best seen in the Lake Creek inflow thermograph records and the data collected by the raft-based monitoring stations. Figures 35 and 36 combine these data for the years 1974 and 1975, respectively. Two typical patterns are illustrated in these plots. First, in 1974 (fig. 35), warm July air temperatures are associated with a July peak in Lake Creek temperatures and water surface temperatures in both lakes. Second, in 1975 (fig. 36), July air temperatures averaged about 1 °C (1.8 °F) lower than in 1974 with a consequent reduction of July water temperatures. This left the August stream and water surface temperatures, which are approximately equal to those of the previous year, as the peak of the annual cycle. These two general patterns were observed with about equal frequency during the study period.

Figure 37 summarizes Lake Creek inflow temperatures and lake water surface conditions based on an averaging of all available data for the years 1972 through 1975. The following general cycle for the ice-free season may be discerned from figure 37: The lakes usually lose their ice cover in the first weeks of May when air temperatures begin to rise sharply. Winds at this time of year tend to be strong and gusty, providing the driving force for the spring overturn which mixes the lakes from top to bottom at a temperature of about 4 °C (39.2 °F). Air temperatures reach their maximum in early July with lake surface and stream temperatures lagging by about a month.

The July-August period tends to be associated with a peak or plateau in water surface and stream temperatures, while air temperatures begin a gradual decline. Lake Creek water enters the upper lake at a temperature about 4 °C (7.2 °F) below that of the lake surface. The upper lake in turn serves as a sort of warming pond for the lower lake, with warm surface water being skimmed off through the shallow channel into the lower lake. Surface temperatures in the lower lake exceed those in the upper by about 2 °C (3.6 °F). Winds during this period are somewhat reduced both in average speed and variability.

The beginning of September coincides with a sharp, steady drop in both water surface and air temperatures, and an increase in the strength and variability of the wind. Fall overturn occurs about 2 weeks earlier in the lower lake than in the upper, reflecting the greater mixing effect of wind over its larger surface area. Ice-on generally takes place in early December on both lakes as average daily air temperatures drop below 0 °C (32 °F). Winter ice cover usually ranges from 600 to 900 mm (2 to 3 ft) in maximum thickness under a snow cover that varies in depth and duration with winter weather conditions.

The cycle described above (fig. 37) reflects the influence of atmospheric conditions on the surface of the lakes. The distribution of this influence within the bodies of water is seen in the pattern of temperature stratification for each lake shown on figure 38 for the years 1974 through 1975. Figure 38 is based on temperature profiles measured with an electronic multiparameter probe during monthly surveys. The cycle of surface temperatures here is much the same as that noted on figures 35 through 37, including the occurrence of July and August peaks in alternate years. Both lakes exhibit a typical dimictic temperature cycle characterized by direct summer stratification, inverse winter stratification, and isothermal conditions during the spring and fall overturns.

The seasonal pattern of temperature stratification within Twin Lakes is generalized on figure 39, which is based on averaging temperature profiles obtained from August 1971 through December 1975. Lake Creek's influence on the temperature structure of the upper lake (station 4) is seen most clearly in July, just after the peak runoff, when the cooler stream inflow causes an indentation in the subsurface temperature lines. This cold inflow to the hypolimnion of the upper lake has the effect of increasing the surface-to-15-m temperature differential, thus making summer stratification stronger in the upper lake than in the lower, despite the fact that surface temperatures in the lower lake are higher than those in the upper.

Juday [11] measured water temperatures in Twin Lakes during the months of July and August in 1902

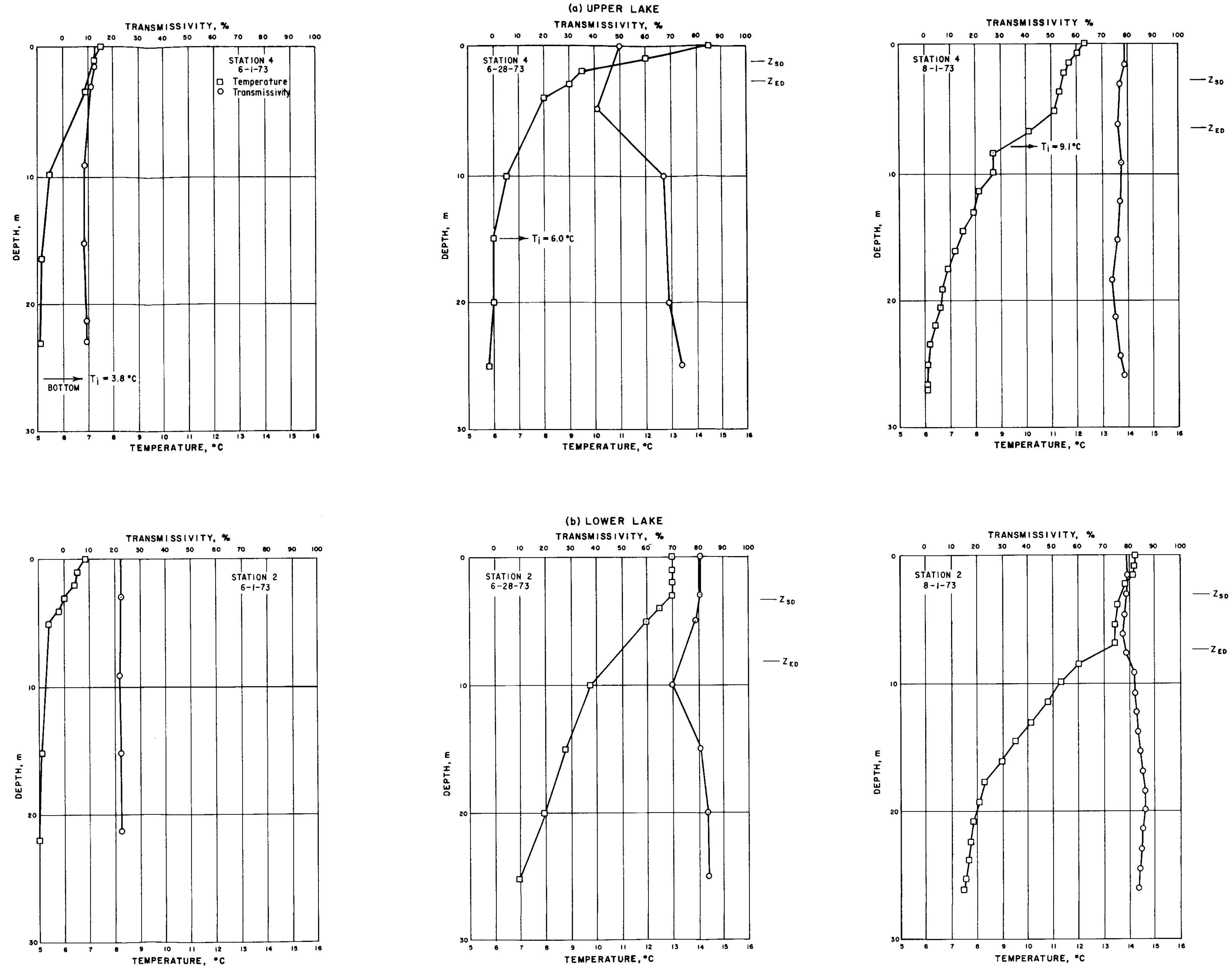


Figure 33.—Horizontal light transmission in Twin Lakes, 1973.

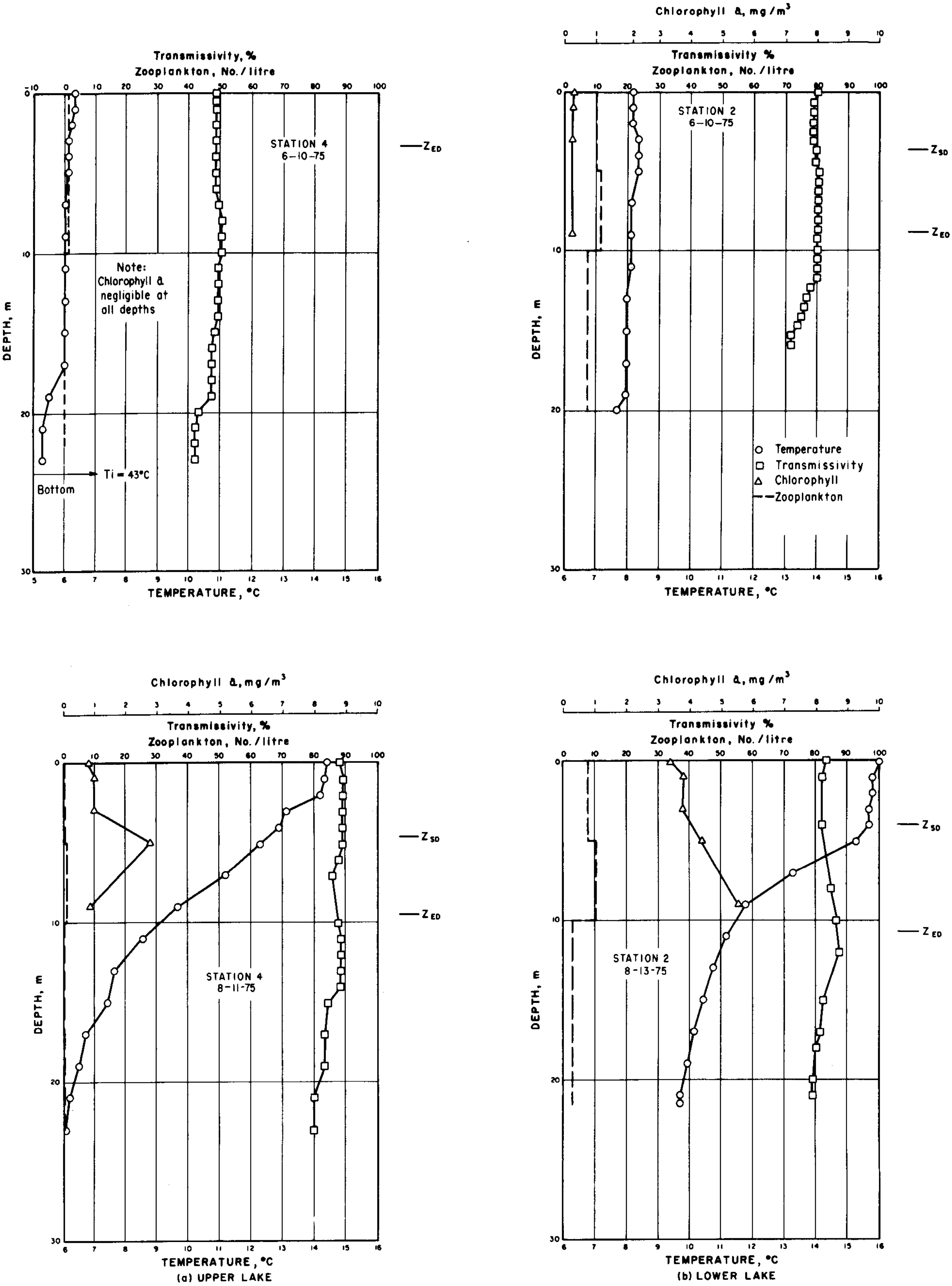
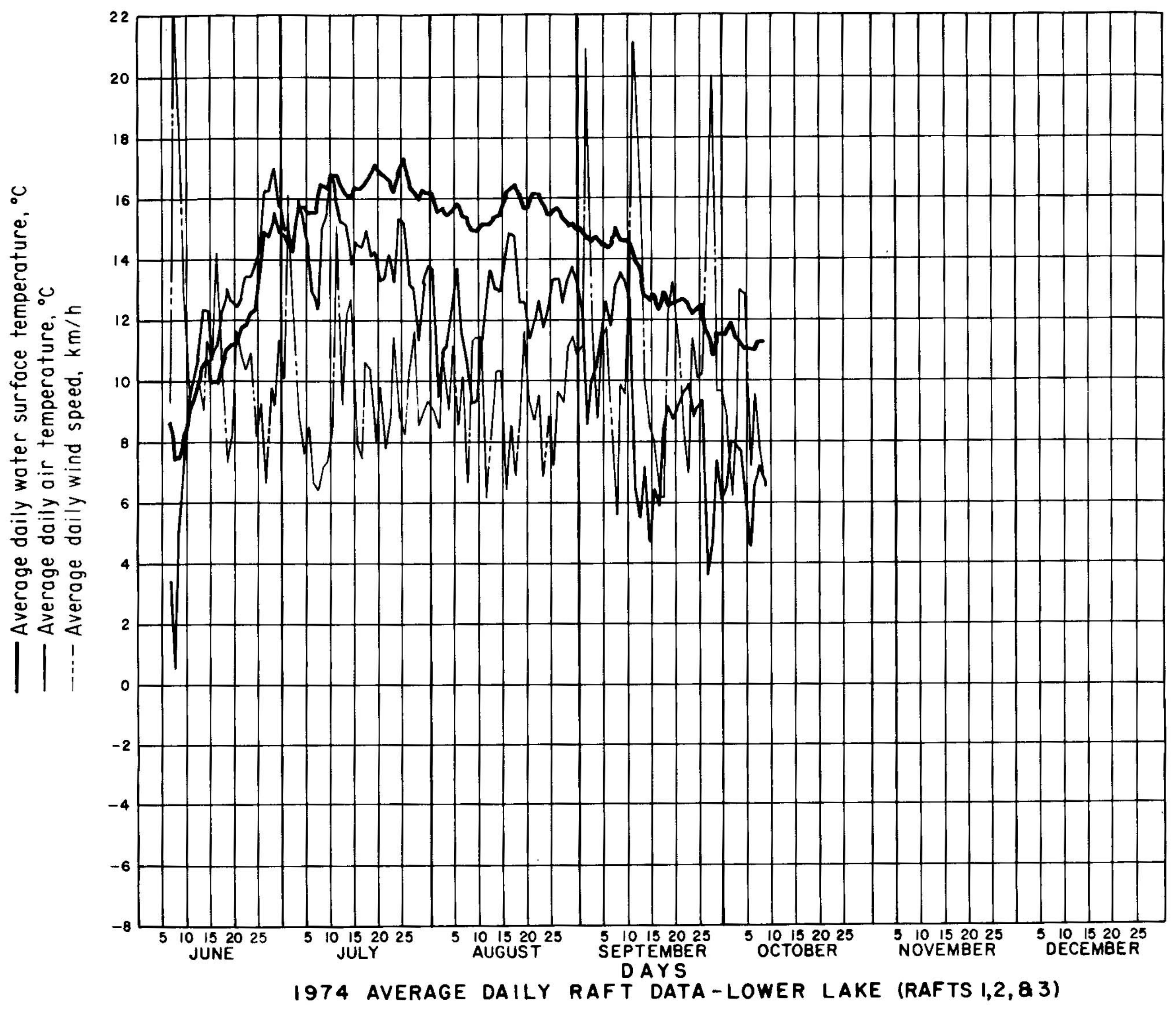
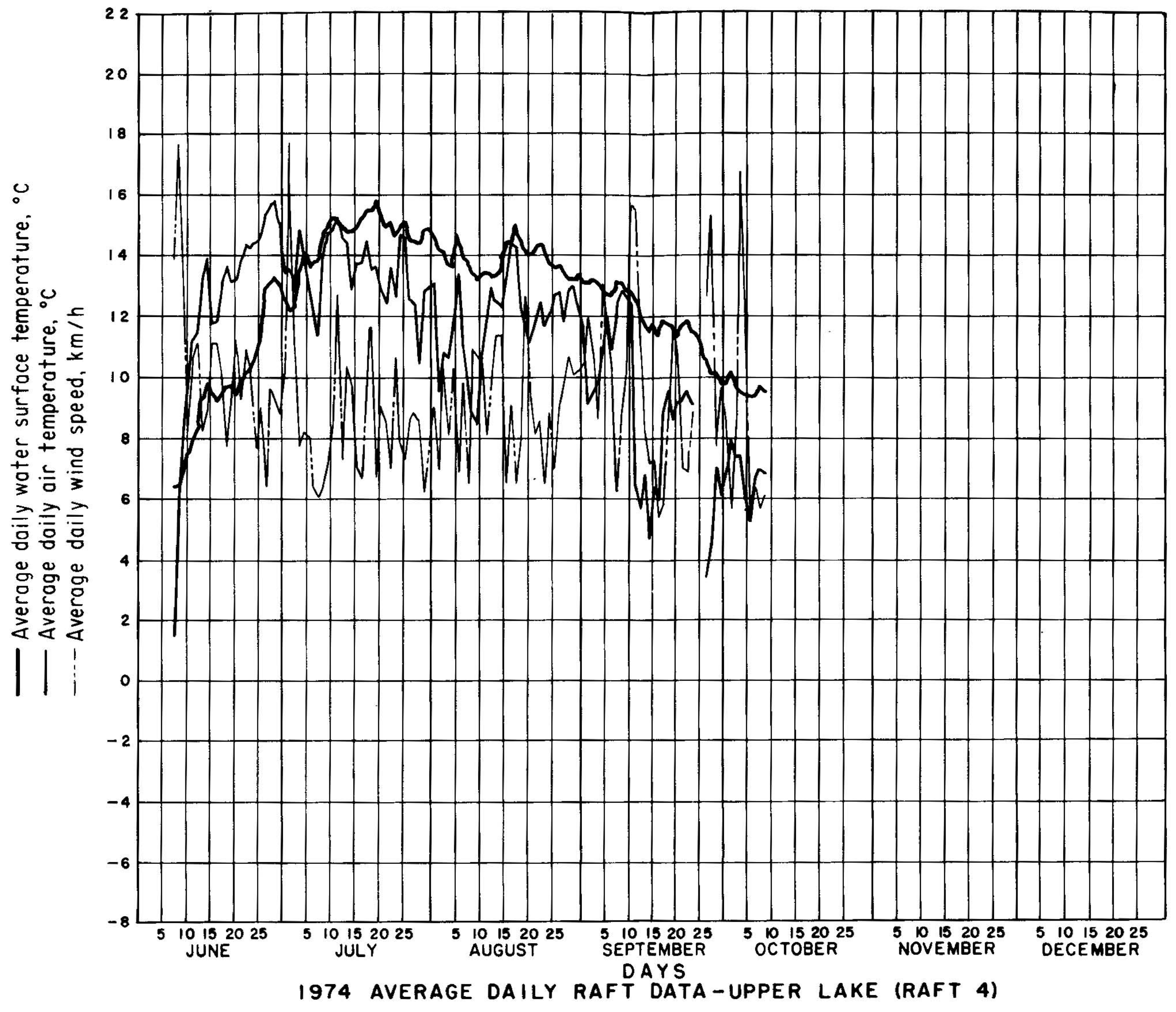


Figure 34.—Horizontal light transmission in Twin Lakes, 1975.





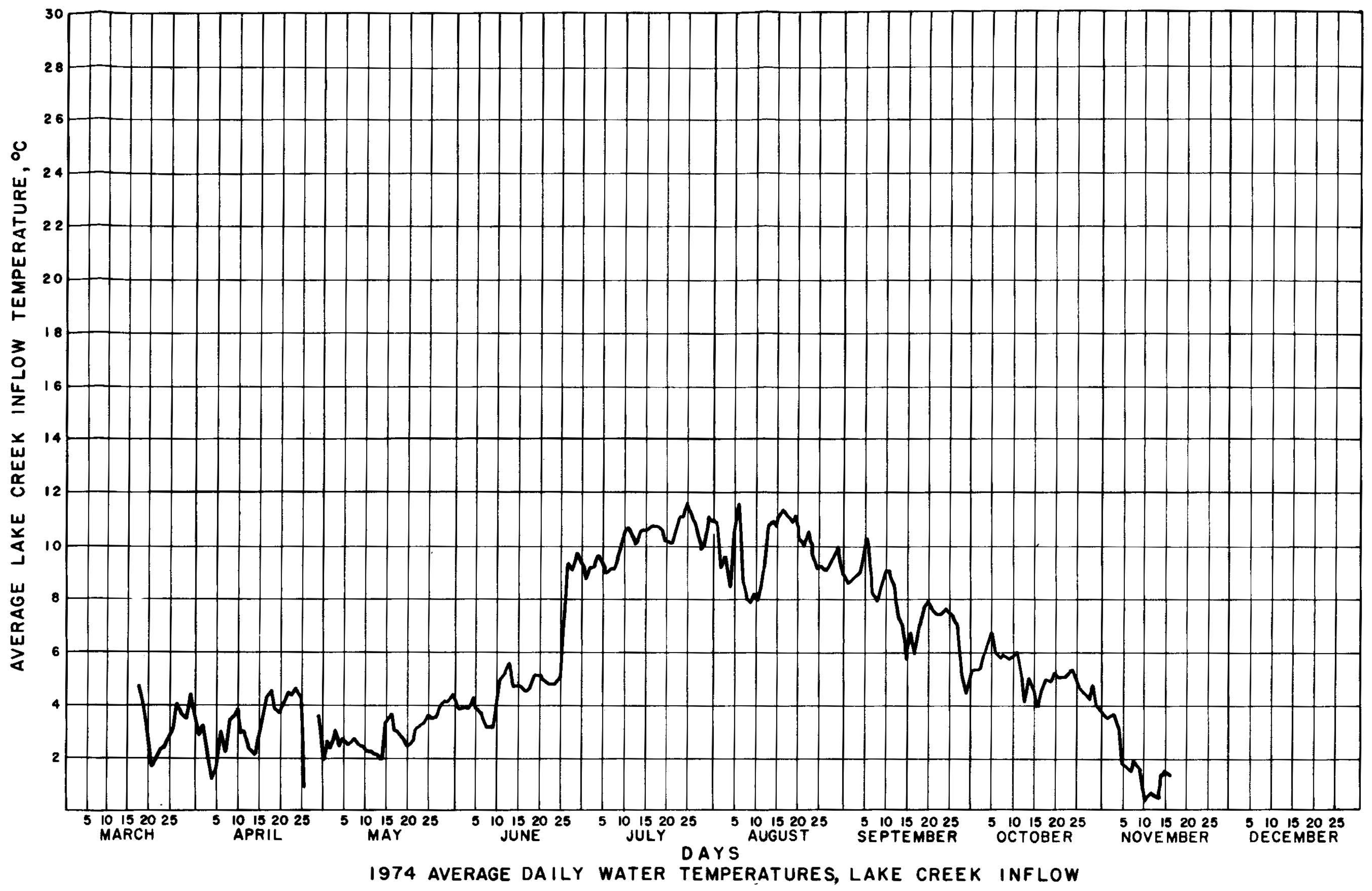
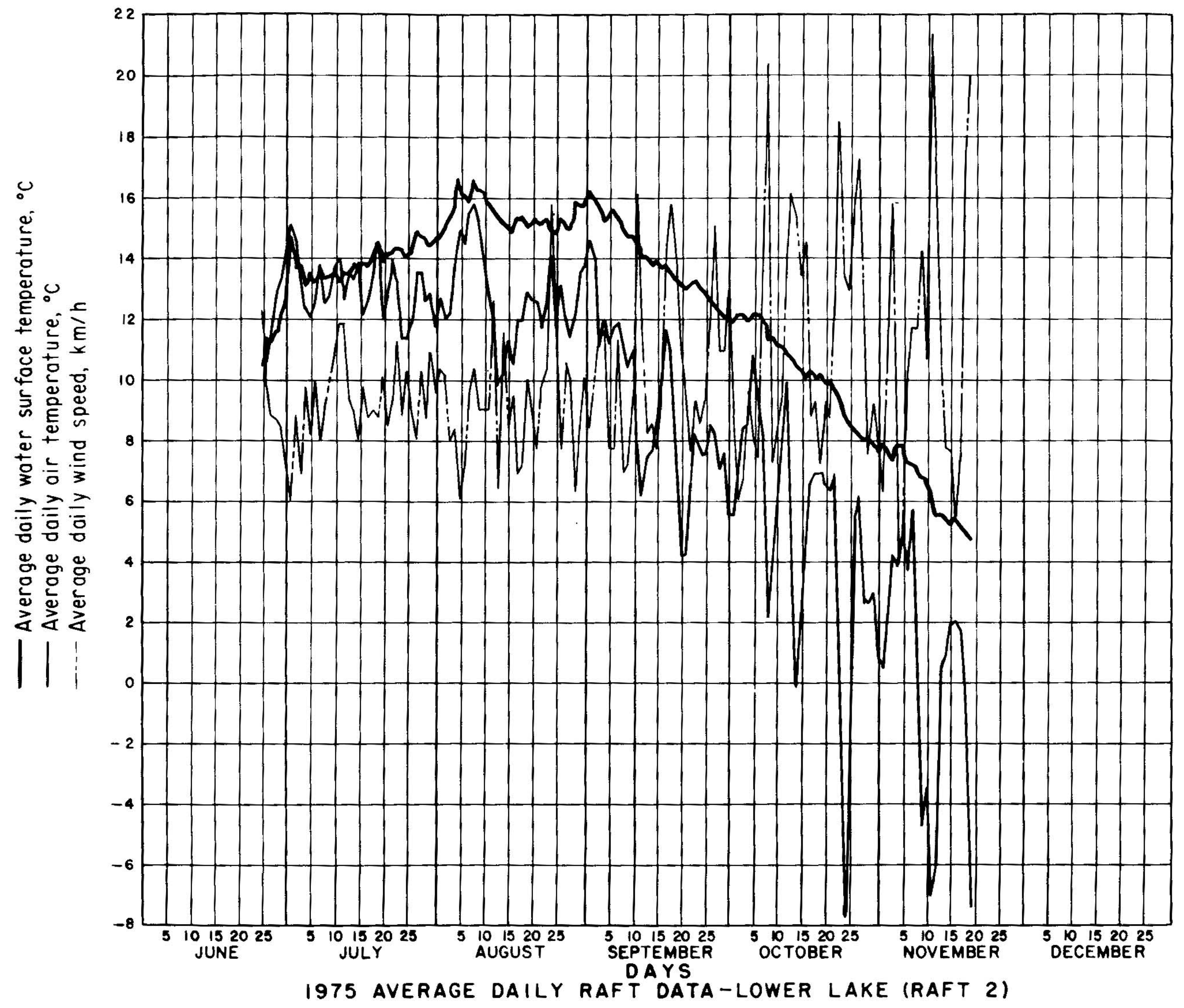


Figure 35.—Inflow temperature and lake surface conditions at Twin Lakes, 1974.



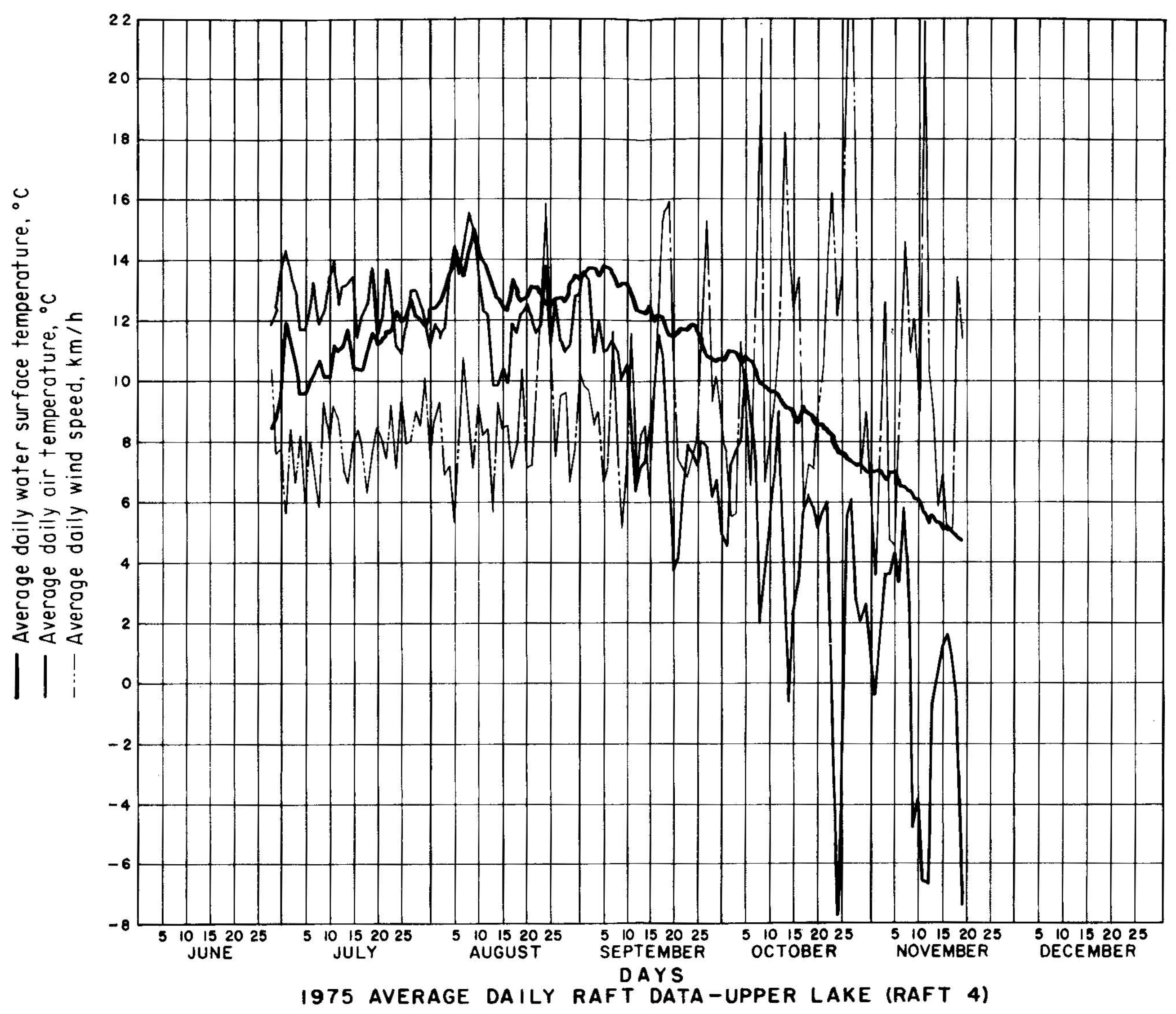
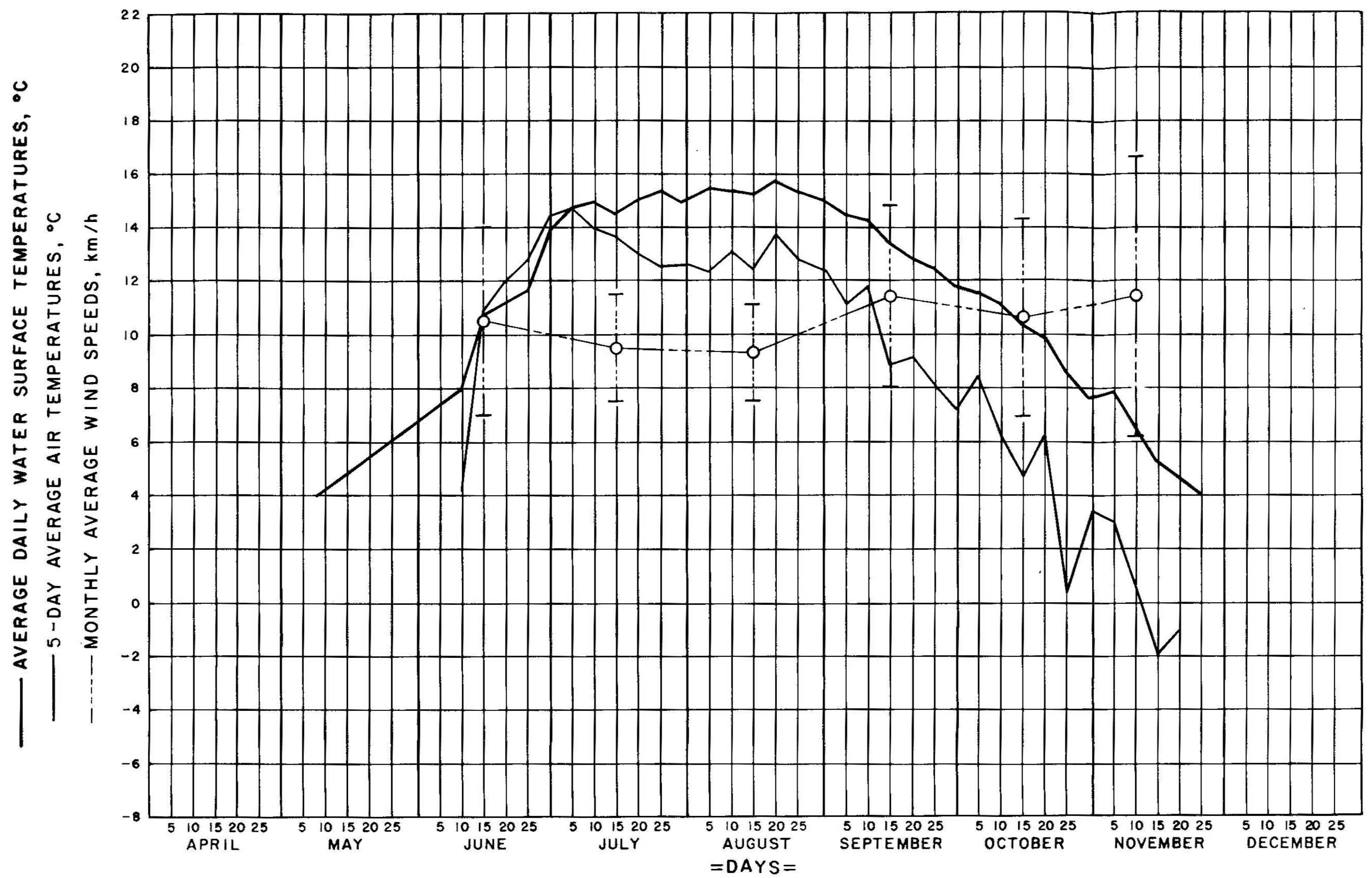
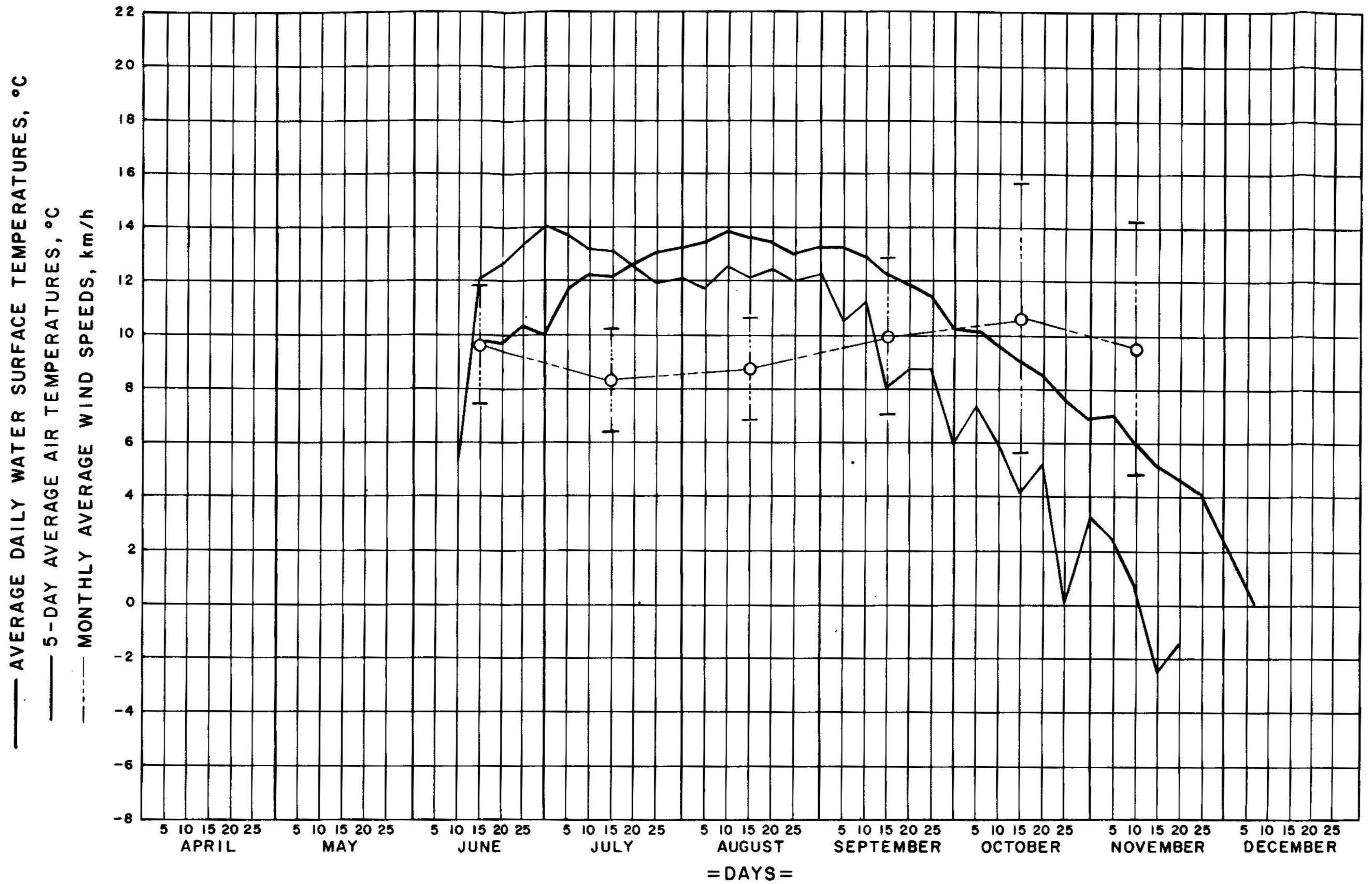


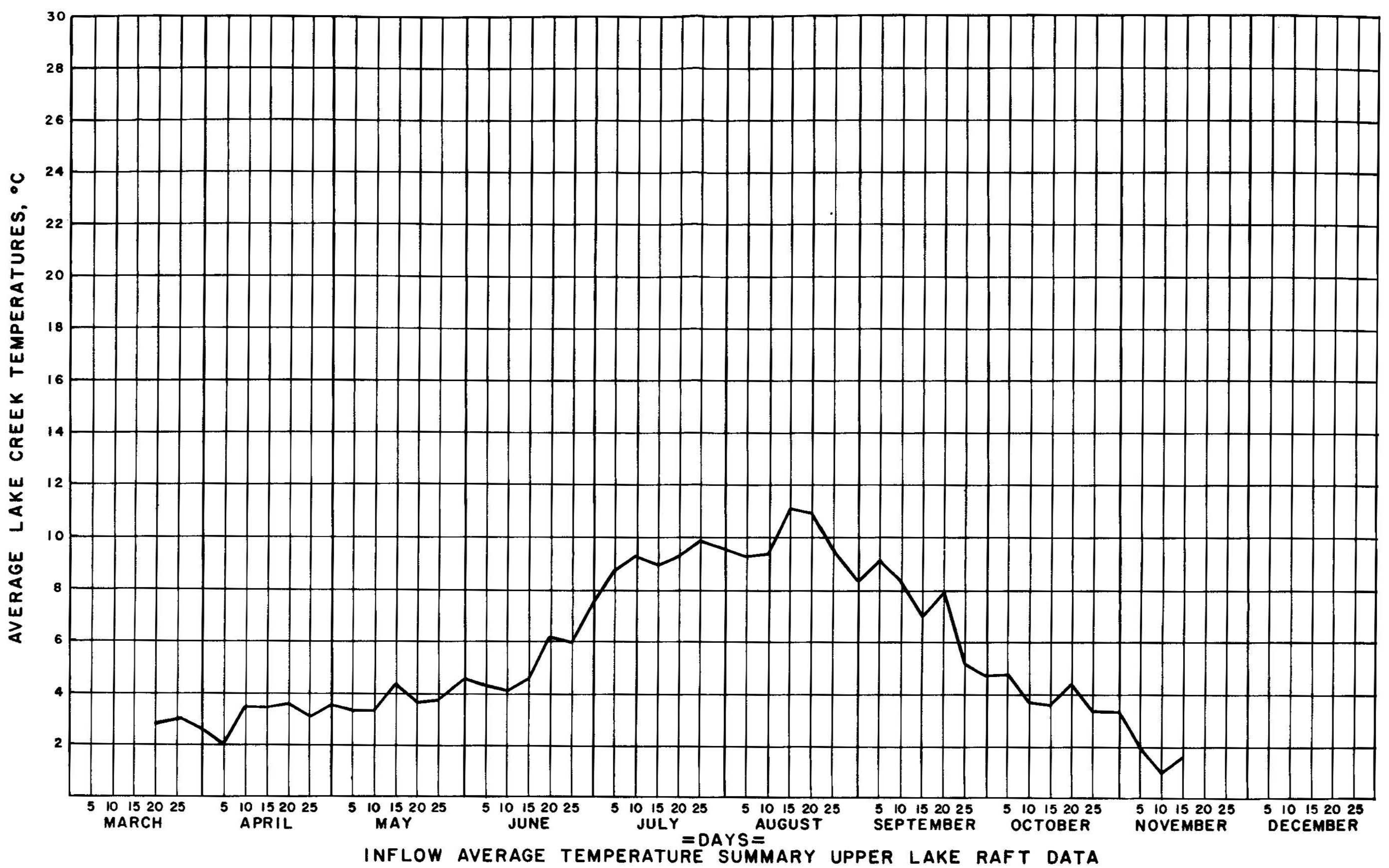
Figure 36.—Inflow temperature and lake surface conditions at Twin Lakes, 1975.



"TYPICAL" RAFT DATA—LOWER LAKE RAFT 1, 2, AND 3
(Based on records for 1972 through 1975)



"TYPICAL" RAFT DATA—UPPER LAKE RAFT 4
(Based on records for 1973 through 1975)



INFLOW AVERAGE TEMPERATURE SUMMARY UPPER LAKE RAFT DATA
(1973–1975)

Figure 37.—Averaged inflow temperature and lake surface conditions at Twin Lakes, 1972-1975.

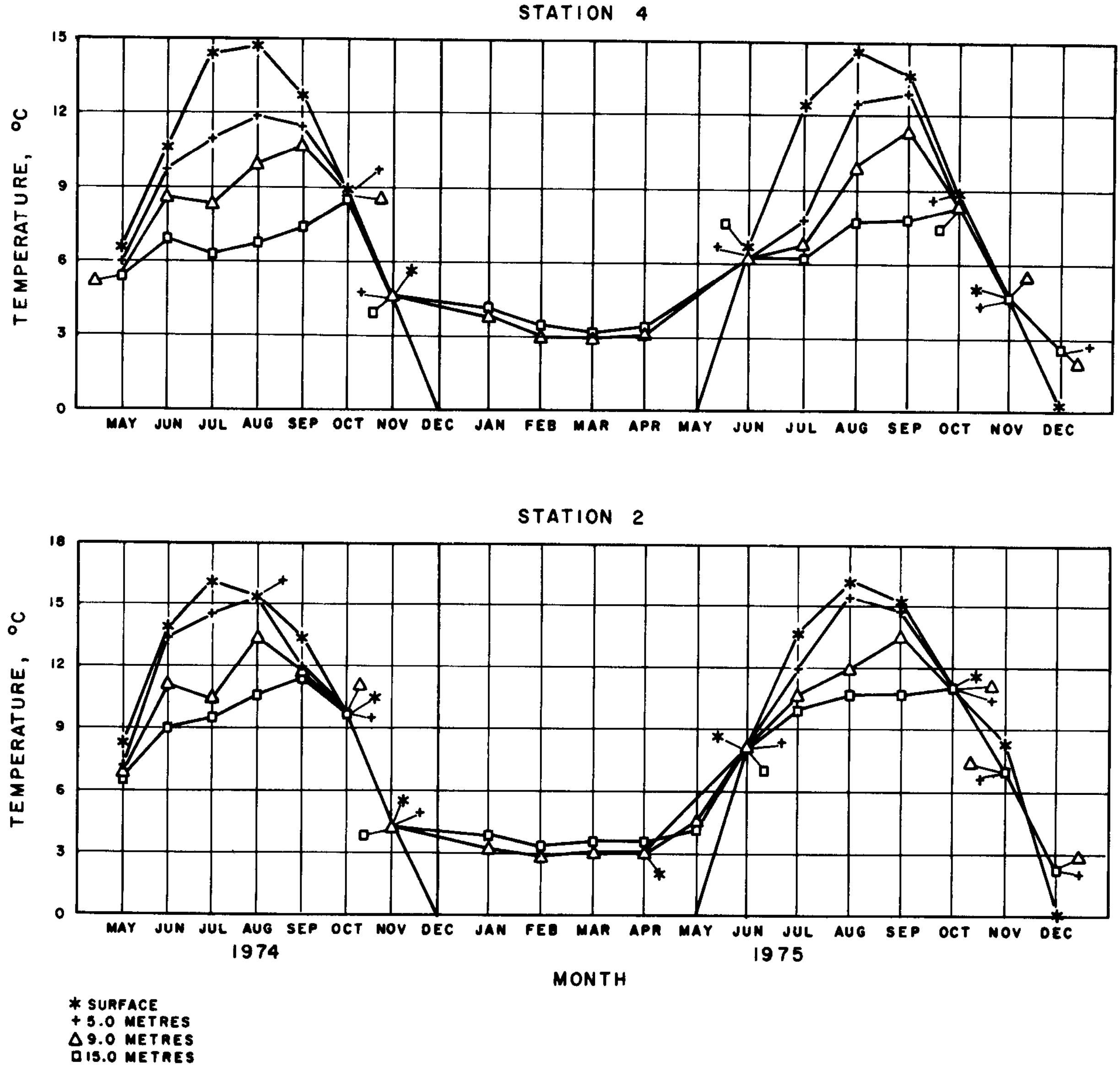


Figure 38.—Temperature at selected depths in Twin Lakes, 1974-1975.

and 1903; his data are included on figure 39 for comparison. Although these temperatures are higher than those observed in the present study, the surface-to-15-m differential in each lake and the average difference between temperatures in the upper and lower lakes are approximately equal to those of recent years. It should be noted that average July and August air temperatures in 1902-1903, as reported by Juday, were about 1.4 °C (2.5 °F) higher than in 1973-1975 and that the average Lake Creek temperature reported for August 1903 was approximately 2.8 °C (5.0 °F) higher than the comparable average for 1973-1975. These warmer air and inflow temperatures, combined with the smaller flows in Lake Creek before the Twin Lakes Tunnel was in operation, might account for the somewhat different stratification pattern indicated by Juday's data (fig. 39).

The temperature structure of Twin Lakes may be summarized by stating that both lakes belong to the category of second-class, dimictic lakes according to Hutchinson's [5] system of classification.

DISSOLVED OXYGEN

From May 1974 through December 1975, D.O. (dissolved oxygen) was measured at least once a month at Twin Lakes. The plotted D.O. data from selected depths for this period (fig. 40) indicate an annual cycle that generally parallels the temperature cycle (fig. 38). During periods of summer and winter thermal stratification, D.O. becomes increasingly depleted with depth, while the free circulation of spring and fall overturns recharges the entire water column. This annual cycle is further illustrated by the three D.O. profiles on figure 41 as examples of the situation at the height of winter stratification in April 1975, just after spring overturn in June 1975, and during maximum summer stratification in August of the same year. In general, D.O. levels remain adequate through the year, except on the bottom during periods of strong thermal stratification. Winter hypolimnetic oxygen levels are especially low, even reaching zero on the bottom of the upper lake in April 1975.

Since the bottom zone of both lakes is most critical with respect to oxygen depletion, all available D.O. observations within 1 m (3.28 ft) of the bottom were averaged over the entire study period, from 1971 to 1976, and are presented as mean monthly values on figure 42. Extreme high and low bottom D.O. observations for each lake are also included on figure 42. While the overall monthly patterns are similar, there are important differences evident between the upper and lower lakes. Bottom D.O. levels tend to be more depleted in the upper lake than in the lower during the winter months. A heavy deposit of allochthonous organic debris, probably the remains of the extensive marshy meadow mentioned by earlier investigators, covers the bottom of the upper lake. This debris, which is not present in the lower lake to any great extent, would have the effect of increasing the oxygen demand of the bottom sediments of the upper lake in relation to those of the lower. Depending on the length and severity of the winter, this higher demand would account for a more extreme oxygen depletion in the upper lake (Maguire [29], Smith and Justice [30]). During the summer months, however, bottom D.O. levels are higher in the upper lake than in the lower. This situation is probably attributable to the oxygenating effect of the Lake Creek inflow, which is not only greater during these months, but also colder than the lake waters, and therefore plunges to the bottom of the upper lake. The lower lake, lacking this oxygenating inflow, tends to exhibit greater oxygen depletion during the summer months, with D.O. dropping to levels comparable to those observed during the winter. The minimum D.O. observed to date in the lower lake occurred in September 1972, just before the fall overturn and at the height of summer stagnation (fig. 42). The minimum D.O. yet observed in the upper lake was zero at the bottom in April 1975.

Bottom D.O. observations for 1975, expressed as percents of the saturation values for the lake surface elevation and the associated bottom water temperatures (Hutchinson [5], Dixon [31]), are graphed on figure 43. The pattern here is similar to that noted in the mean monthly D.O. plots (fig. 42). Two points more clearly defined on figure 43, however, are the times of spring and fall overturn, when the lakes circulate freely and bottom D.O. reaches, and even exceeds, 100 percent of saturation. As data on figure 43 indicate, spring overturn occurs earlier in the upper lake than in the lower; the upper lake circulates freely for a longer period and lags in fall overturn. The supersaturated oxygen levels, attained in the upper lake during spring and early summer runoff, appear to preclude the extreme summer oxygen depletion noted in the lower lake.

Associated with the hypolimnetic oxygen depletion in Twin Lakes in the late winter of 1974-75 were declines in the Eh (oxidation-reduction potential) (fig. 49) and pH (hydrogen ion concentrations (fig. 47). The strongly reducing environment that accompanied the complete loss of D.O. from the bottom waters of the upper lake in April 1975 was conducive to the release of soluble iron and manganese from

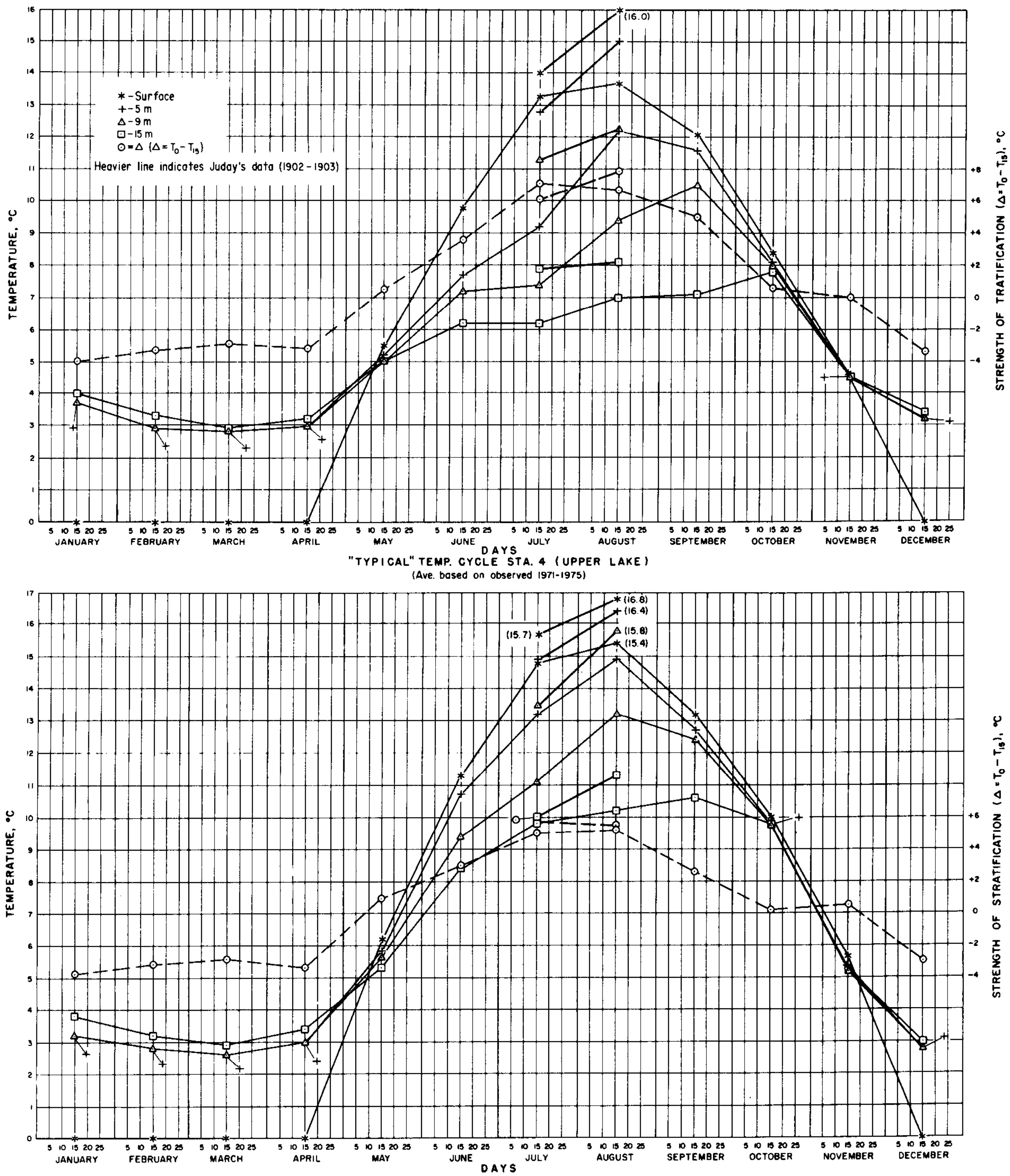


Figure 39.—Averaged temperature at selected depths in Twin Lakes, 1971-1975.

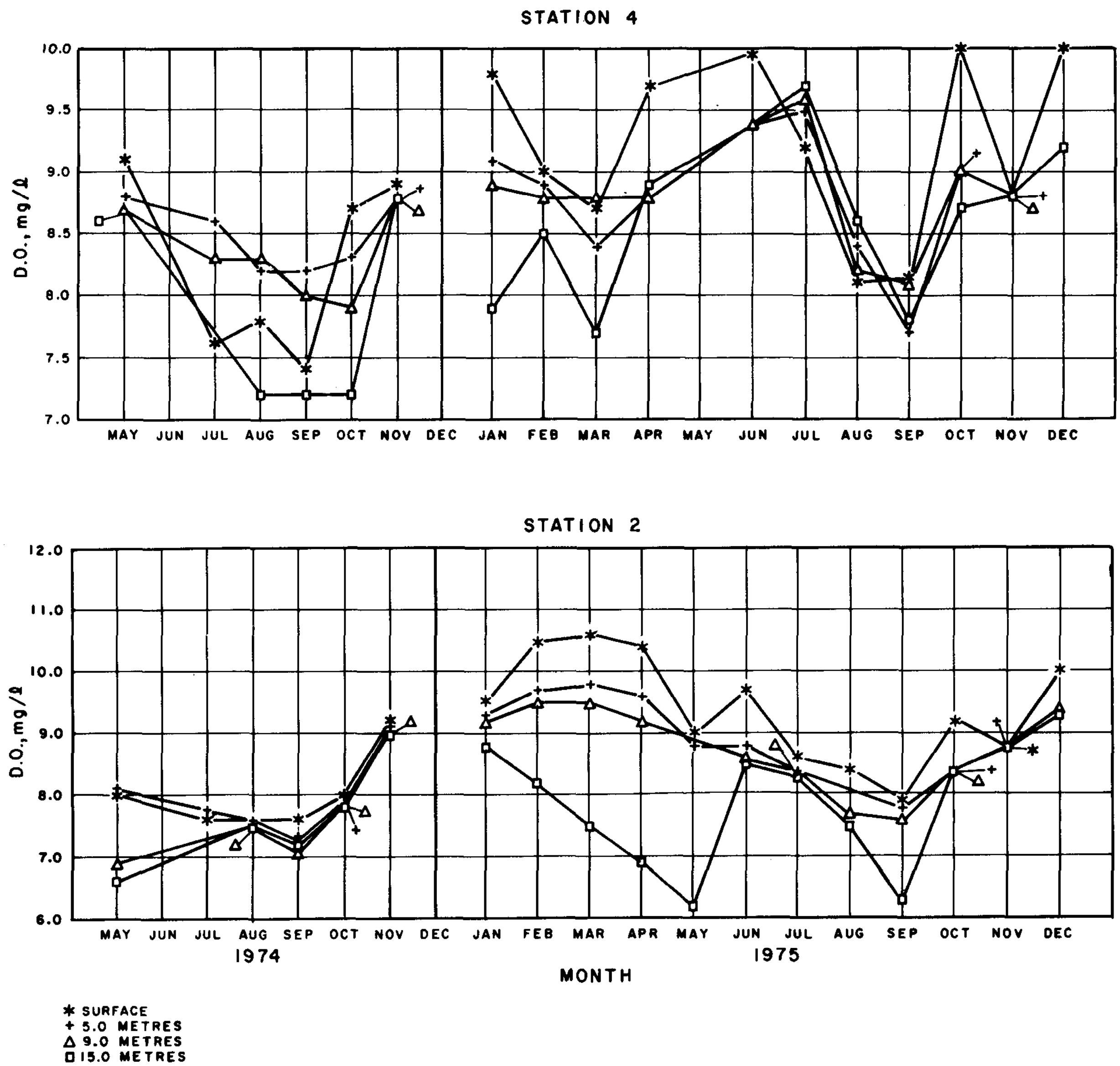


Figure 40.—Dissolved oxygen at selected depths in Twin Lakes, 1974-1975.

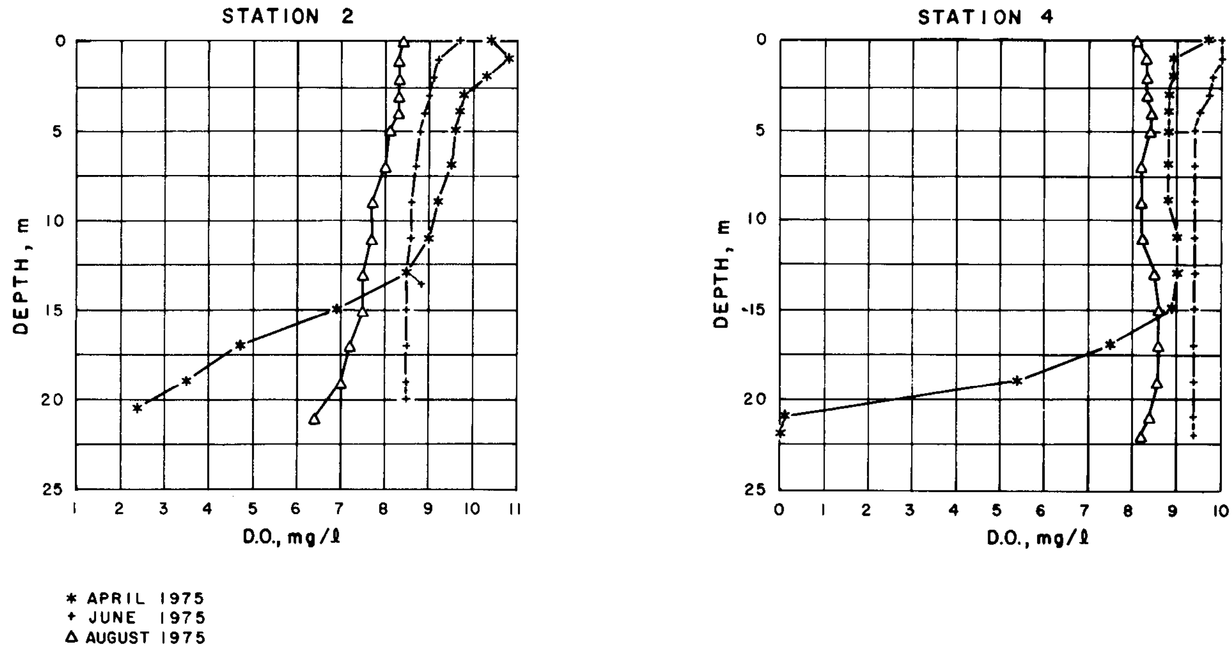


Figure 41.—Selected dissolved oxygen profiles from Twin lakes, 1975.

the bottom sediments. As will be discussed in the following sections on sediments and water chemistry, the sediments of Twin Lakes contain a large concentration of heavy metals, including iron and manganese, and the loss of oxygen at the sediment-water interface was accompanied by a significant increase of these metals in the overlying water.

SEDIMENTS

Description

Juday [11] characterized the bottom sediments of Twin Lakes as being "sandy and gravelly" in the shallower areas, with a "marly deposit" covering the bottom in deeper water. Mineral identification and gradation analysis performed on four samples of unconsolidated material from the bottom of the lower lake in 1972 indicated that the deeper sediments are actually "very fine-grained rock flour," produced by glacial action and deposited in Twin Lakes by tributary streams (Klein [32]). Scuba divers from the Bureau's Lower Missouri Region have noted that the movement of swim fins within about a metre of the bottom is sufficient to stir this fine material and bring it into suspension "for days" (LaBounty, et al. [33]).

Petersen and Ekman dredge samples from Twin Lakes reveal a general three-layered profile in the bottom sediments. The top of a typical dredge sample is covered with a thin layer of orange-colored flocculant material. The second layer is a brown material about 30 mm thick, and the third layer is approximately 90 mm of a gray-black material of "pudding-like" consistency. Upper lake sediments differ from those in the lower lake in that they contain a large amount of woody debris. An average sedimentation rate of 0.63 mm per year has been estimated for Twin Lakes (Bergersen [26]).

Sediment Chemistry

In a recent bacteriological survey of Twin Lakes, Deason [34] found iron and sulfur bacteria in all bottom samples, with iron bacteria being more numerous in the lower lake than in the upper [2400 MPN/g (most probable number per gram) at station 2 compared to 40 MPN/g at station 4]. Deason noted that the "orange flocculant material" on top of the sediment averaged 9 percent iron by dry weight, as compared to 1 percent for the rest of the sediment.

Bergerson [26] used a series of frozen core samples to investigate recent sedimentation rates, sediment composition with depth, and the biological history of recent sediments.

Two general conclusions based on his work are:

1. High concentrations among the 48 elements surveyed were more often found in the upper lake

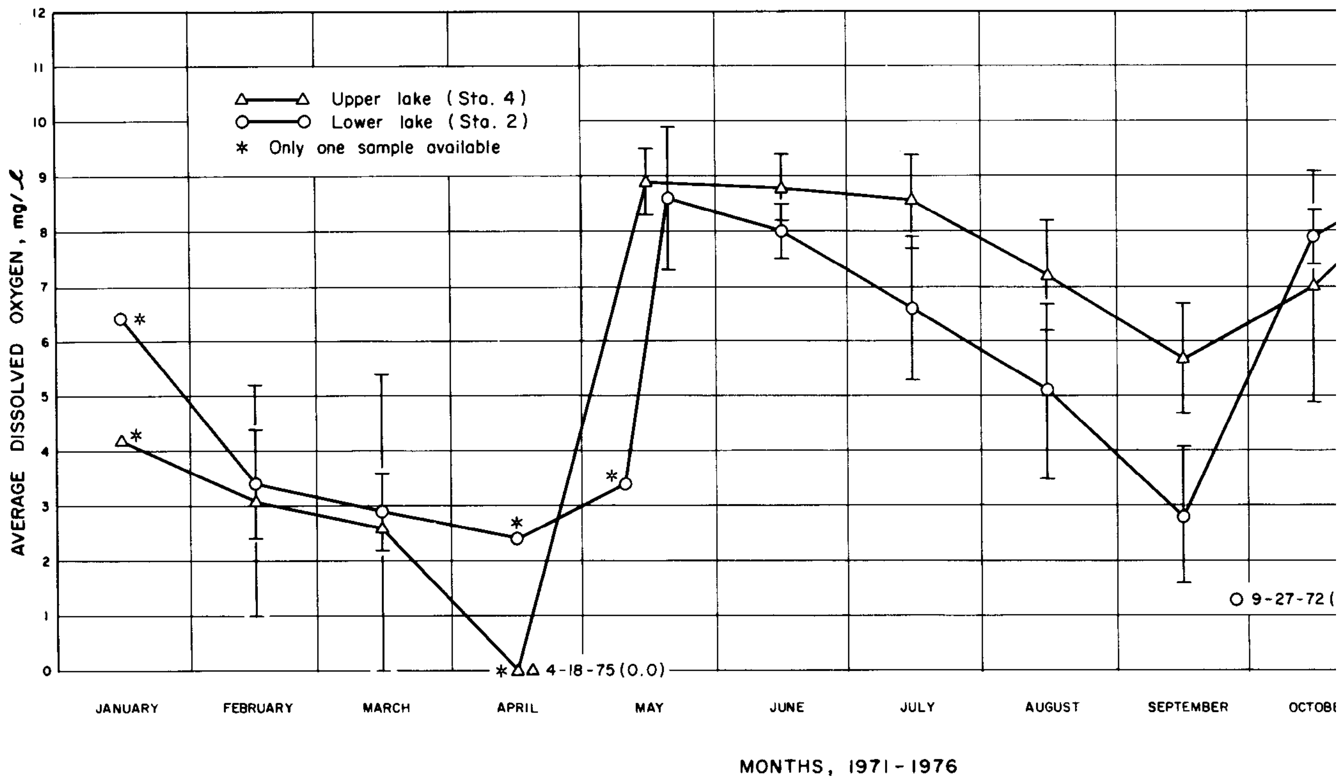


Figure 42.—Mean monthly dissolved oxygen levels on the bottom of Twin Lakes, 1971-1976.

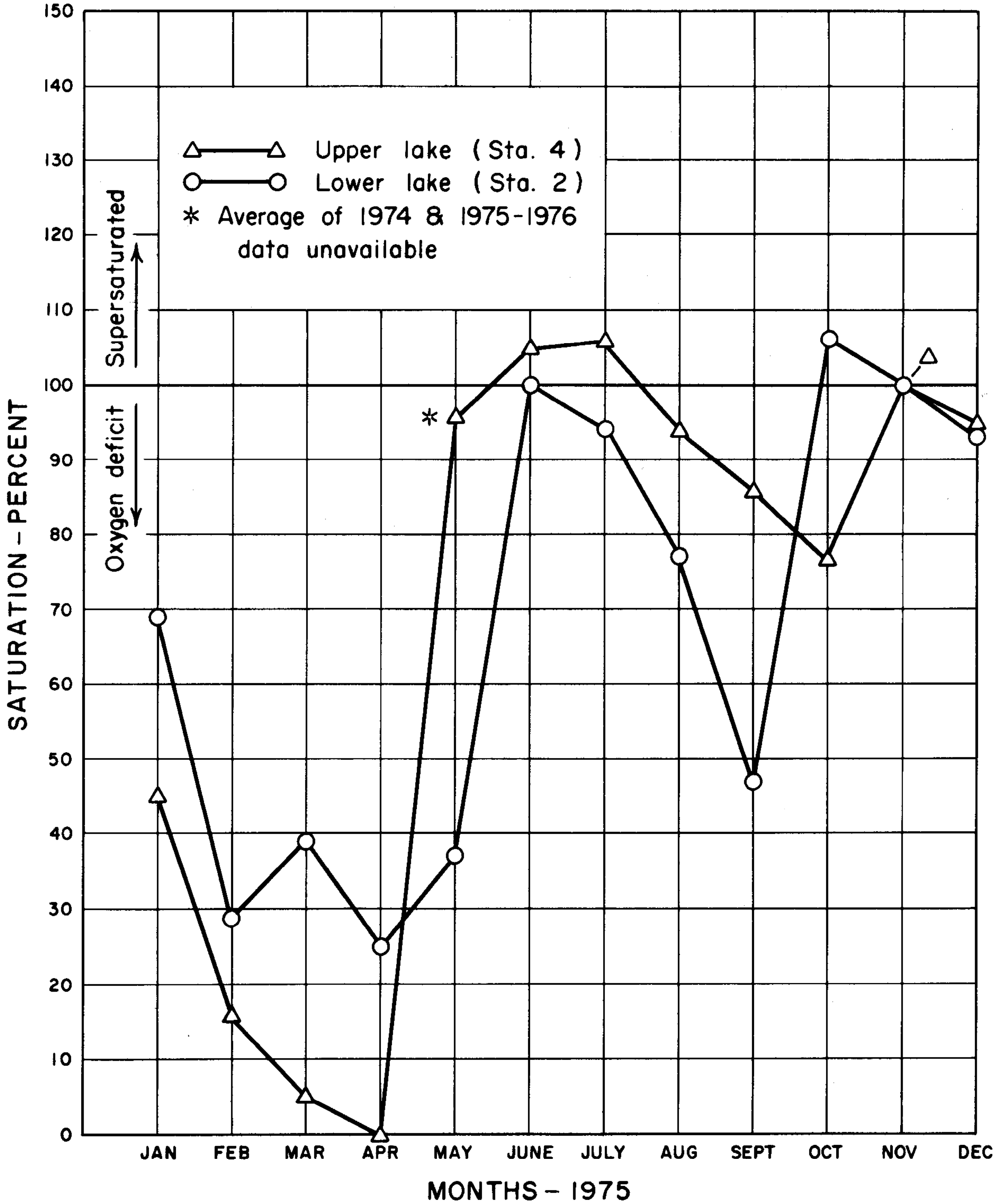


Figure 43.—Percent dissolved oxygen saturation of bottom water in Twin Lakes, 1975.

than in the lower, suggesting that, at least in recent times, the upper lake has served as a "nutrient trap in the Twin Lakes system."

2. Distinct increases in total carbon, copper, zinc, silver, and the ratio of araphidineae to centrales diatoms in the sediments of the upper lake coincide closely with the beginnings of heavy human activity in the watershed, approximately 100 to 125 years ago.

In this study, interest has centered on the heavy metal content of the sediments and, accordingly, dredge samples were analyzed for iron, manganese, zinc, copper, lead, and molybdenum on a monthly basis from June 1974 through June 1975. Silver and cadmium were added to the list beginning in January 1975. Results of these analyses are shown on figure 44.

Iron is the most abundant of the eight heavy metals investigated, followed by manganese, zinc, copper, lead, silver, and cadmium (fig. 44). No molybdenum was detected in the samples analyzed. With the exception of molybdenum, these results are in general agreement with the conclusions in Bergersen [26], both as to relative abundance and order of magnitude of concentrations. Bergersen detected approximately 0.006 mg/g molybdenum in his survey of composited cores from both lakes.

Table 6 includes a more detailed comparison of the average sediment heavy metal concentrations in Twin Lakes. This comparison shows the upper lake sediments to be richer in iron and copper, while those of the lower lake contain larger amounts of manganese, zinc, lead, silver, and cadmium.

With the possible exception of lead and cadmium, however, the average concentrations in the two lakes are so similar as to make conclusions as to relative enrichment difficult. Of the eight metals surveyed, only lead, cadmium, and iron are consistently higher in concentration in one lake or the other in every monthly sample. Bergersen [26] reported results of a detailed survey of the relative abundance of copper, lead, silver, and zinc in the two lakes. The upper lake was reported to be relatively enriched in all but lead.

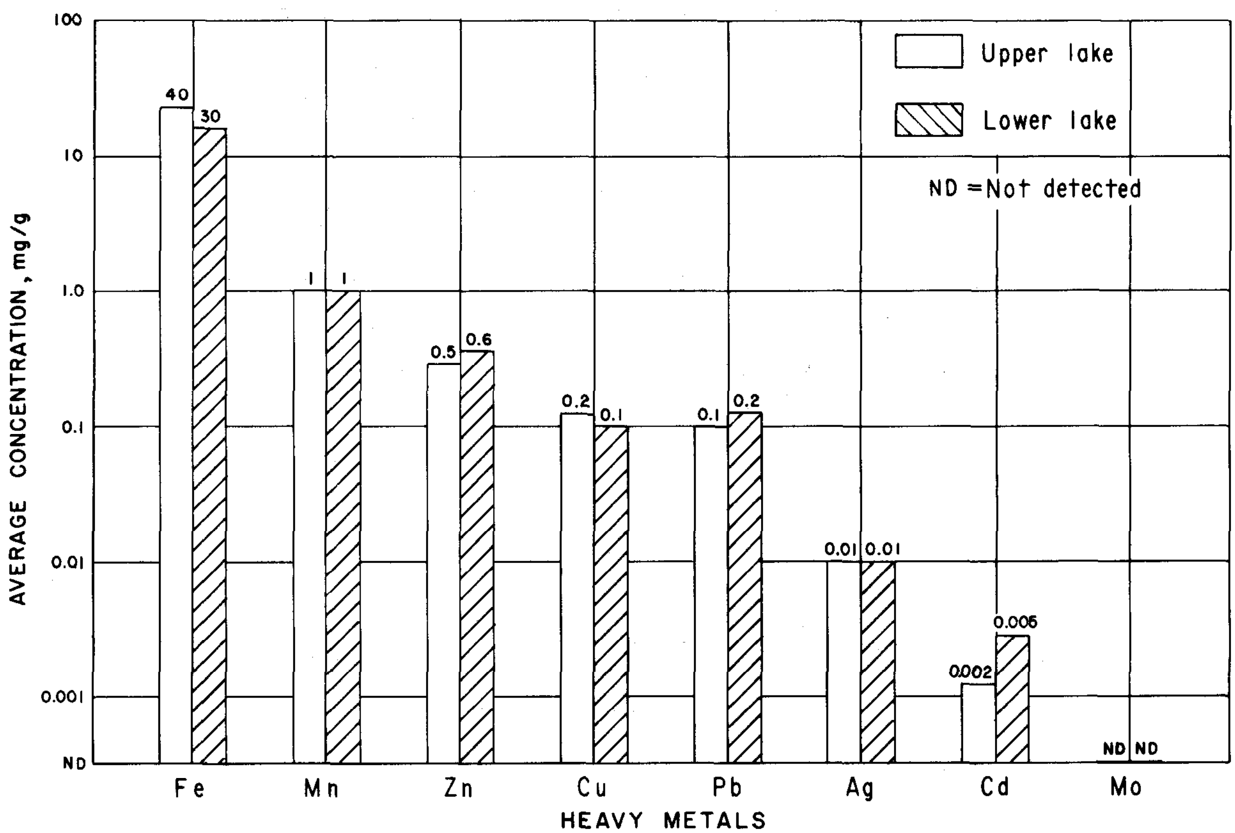


Figure 44.—Average concentrations of heavy metals in Twin Lakes sediments—order-of-magnitude values.

Table 6.—*Comparison of sediment heavy metal concentrations*

Location	Dry weight, mg/g							
	Iron	Manganese	Zinc	Copper	Lead	Silver	Cadmium	Molybdenum
Twin Lakes, Colo.								
Upper lake	38.10	1.09	0.510	0.157	0.07	0.010	0.002	ND
Lower lake	31.81	1.33	0.572	0.141	0.16	0.012	0.005	ND
Turquoise Res., Colo.	13.3	0.2	0.56	0.06	0.16	0.009	0.011	-
Clear Creek Res., Colo.	17.4	0.6	0.14	0.04	0.06	0.002	0.002	-
Pueblo Res., Colo.[1]	20.77	0.45	0.394	0.037	0.10	-	0.004	ND
Ten Wisconsin Lakes (mean concentrations)[4]	-	-	0.076	0.028	0.029	-	0.002	-
*Southern part of Coeur d'Alene Lake, Idaho[2]	-	-	4.8	0.125	3.5	-	-	-
*Arkansas River at California Gulch, Colo.[3]	30.0	1.3	6.5	0.375	2.45	-	-	ND

* Area polluted by mine wastes.
[1] Adapted from Herrmann and Mahan [35]
[2] Adapted from Maxfield, et al. [36]
[3] La Bounty, et al. [37]
[4] Adapted from Iskander and Keeney [38]

Once again, however, the concentrations in the sediments of the two lakes were very similar, except for lead.

Ferromanganese concretions (fig. 45) have been found on one occasion in Twin Lakes, in a dredge sample from North Bay in the lower lake (fig. 3) at a depth of approximately 15.5 m. The bottom sediments in this area are granular material, rather than the glacial flour which covers the deeper portions of the lake. Petrographic analysis of the concretions showed them to be composed chiefly of amorphous to poorly crystalline iron oxides in concentric layers around nuclei of fine-grained quartz and feldspar (Backstrom [39]).

The concretions were also analyzed for heavy metals and found to contain 387.5 mg/g iron, 20.5 mg/g manganese, 0.60 mg/g lead, 0.53 mg/g zinc, and 0.22 mg/g copper (Backstrom [39]).

Similar concretions have been reported in Lakes Michigan, Ontario, and Erie, as well as smaller lakes in Sweden, Finland, Canada, and the northern parts of England and the United States. (See Gorham and Swaine [40], Harriss and Troup [41], Sozanski and Cronan [42]).

These data seem to indicate the sediments of the upper lake to be relatively enriched in iron and copper, while those of the lower lake contain larger amounts of lead and cadmium. Concentrations of manganese, zinc, and silver in the sediments of both lakes are very similar, with perhaps some relative enrichment in the lower lake.

Samples used for heavy metal analysis in this study were collected with dredges while those from other studies reported here were collected with a corer. This means that samples collected with a dredge represent a composite of approximately the upper

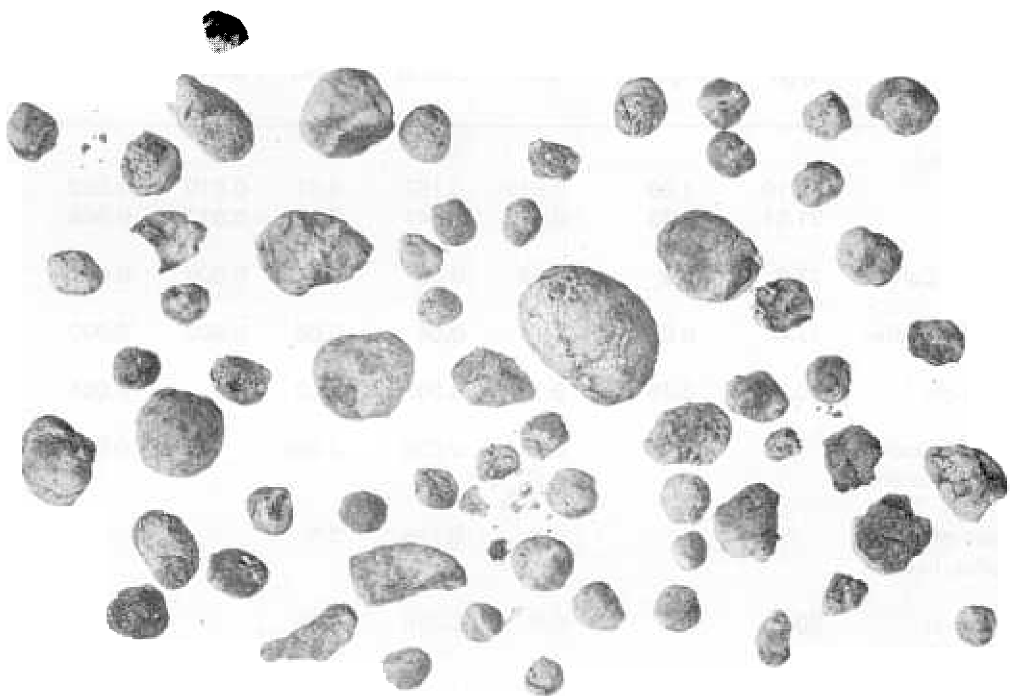


Figure 45.—Ferromanganese concretions from North Bay, the lower lake (X 2).

150 to 200 mm of sediment. Because of this difference in sampling technique, all data from core samples, including those reported from Bergersen [26], have been averaged over the length of the core before being used for comparison.

The sediments of Twin Lakes are compared with those of other waters, on the basis of heavy metal concentrations, in table 6. All three reservoirs cited are located in the Arkansas Valley of Colorado: Turquoise and Clear Creek on parallel tributaries of the Arkansas north and south, respectively, of Twin Lakes, and Pueblo on the main river itself some 175 km downstream. In relation to these three Colorado reservoirs and the 10 Wisconsin lakes, Twin Lakes sediments are enriched in iron and, to a lesser extent, in manganese and copper. The magnitude of this enrichment is, in fact, more comparable to that exhibited by the Arkansas River at its confluence with California Gulch near Leadville, Colo., in the case of iron and manganese, and to the southern part of Coeur d' Alene Lake, Idaho, in the case of copper. Both the last two mentioned waters are considered polluted by mine wastes (LaBounty, et al. [37], Maxfield, et al. [26]). Twin Lakes sediments, on the other hand, contain much less zinc and lead than the polluted waters.

Williams, Aulenbach, and Clesceri [43] report extreme high values of sediment concentrations of cadmium, copper, and zinc from lakes in the Adirondack region of New York that are an order of magnitude less than the lowest values shown in table 6. They also note that their results compare closely with those from other lakes in granitic Precambrian bedrock basins in northeast Minnesota and southern Norway. On the other hand, Braidech and Emery [44], in their study of trace elements in various water supplies in the United States, report order-of-magnitude higher values of copper and zinc in the water supplies of Denver and Helena, with sources in the mineralized Rocky Mountains, as compared with Minneapolis, New York City, and Boston, with sources in uplands of ancient crystalline rock. The above comparisons, coupled with the relative insignificance of mining operations in the Lake Creek watershed, seem to indicate that the heavy metals which have accumulated in the sediments of Twin Lakes are of natural origin. In fact, as will be discussed in the section on water chemistry, Lake

Creek carries a large amount of heavy metals into Twin Lakes from exposed mineral deposits on its South Fork. Another significant factor is that Twin Lakes are much older than the three reservoirs mentioned in table 6, so that even the top 100 to 200 mm of sediment in the lakes would represent a longer period of deposition and accumulation than comparable thicknesses for the reservoir bottoms.

In summary, the sediments of Twin Lakes are mostly unconsolidated, fine-grained rock flour of glacial origin. These sediments contain a significant accumulation of heavy metals, including iron, manganese, zinc, copper, lead, silver, and cadmium. Iron and copper are relatively more abundant in the sediments of the upper lake, while those of the lower lake are more enriched in lead and cadmium. Apparently, these metals are derived from mineral deposits within the Lake Creek watershed and, while human activities in the past century may have accelerated their erosion and deposition in the lakes, they are not the result of mining operations *per se.*

WATER CHEMISTRY

The water chemistry of Twin Lakes is intimately related to that of its sediments and tributaries, particularly Lake Creek, and is strongly influenced by such physical parameters as temperature and D.O. levels. The following discussion covers both Lake Creek and Twin Lakes water chemistry, including chemical indexes and major ions.

The subsection on heavy metals includes a detailed consideration of chemical interactions at the sediment-water interface.

Chemical Indexes

In Twin Lakes, pH is generally neutral to slightly basic. Figure 46 shows pH at selected depths within both lakes from May 1974 through December 1975. Peaks in pH (i.e., basic conditions) generally occur in the upper layers at times of maximum summer stratification. An exception to this general trend may be noted in the upper lake (station 4 on fig. 46) during the summer of 1975.

Slightly acid conditions (pH $<$ 7.0) occur in the lower levels of both lakes during both summer and winter stratification periods. Figure 47, showing the monthly variation in pH of water within the bottom metre of both lakes during 1975, illustrates this point and indicates these acid conditions to be more pronounced during winter stagnation.

Since August 1974, Eh has been measured in the waters of Twin Lakes. Representative Eh profiles for both lakes are shown on figure 48. The annual cycle suggested here is one of lowered redox potentials throughout the water column during summer and winter stagnation, with recovery at spring and fall circulation. In the lower lake this recovery is generally "elastic"; i.e., the overall degree of raising and lowering of redox potentials is approximately the same from season to season. The upper lake, however, exhibits a wider range in Eh from season to season. In general, spring redox potentials are higher than the fall, and winter potentials drop lower than those of summer. The abrupt drop in Eh at the bottom of the winter profile is especially interesting because it indicates the development of a reducing environment at the sediment-water interface during winter stagnation.

Figure 49 is a graph of mean monthly redox potentials in the bottom metre of the water columns of both lakes. During the winter of 1974-1975, redox potentials at the bottom of the upper lake fell below 200 to 300 mV, the range in which ferric iron is reduced to the ferrous state (Cole [22]). During the next winter 1975-1976), however, bottom redox potentials in both lakes remained relatively high.

The operating manual (Hydrolab [45]) for the electronic probe with which redox potential was measured states: "At the present time, oxidation-reduction measurements in natural waters can be interpreted only qualitatively. That is, no general approach to quantitative interpretation is known because of the complexities of natural water chemistry and the fact that many oxidation-reduction reactions occurring in natural waters do not reach equilibrium." While the above statement is probably true, especially of pelagic waters, Eh shifts in the profundal waters have been shown to have strong implications for chemical interactions at the sediment-water interface (Hutchinson [5], Hargrave [46], Cole [22]). These implications are discussed in the subsection on heavy metals.

Water samples for complete laboratory chemical analysis were collected at the inflow and outflow of Twin Lakes, as well as at the surface, mid-depth, and bottom of each lake, from April 1974 through May 1975. Mean monthly values of TDS (total dissolved solids) for each segment of the Twin Lakes system during this period are graphed on figure 50. Lake Creek above and below the lakes averages about 85 to 64 mg/l TDS, respectively, which is well below the 120 mg/l suggested as the average TDS of the world's rivers (Cole [22]). Average TDS for Upper

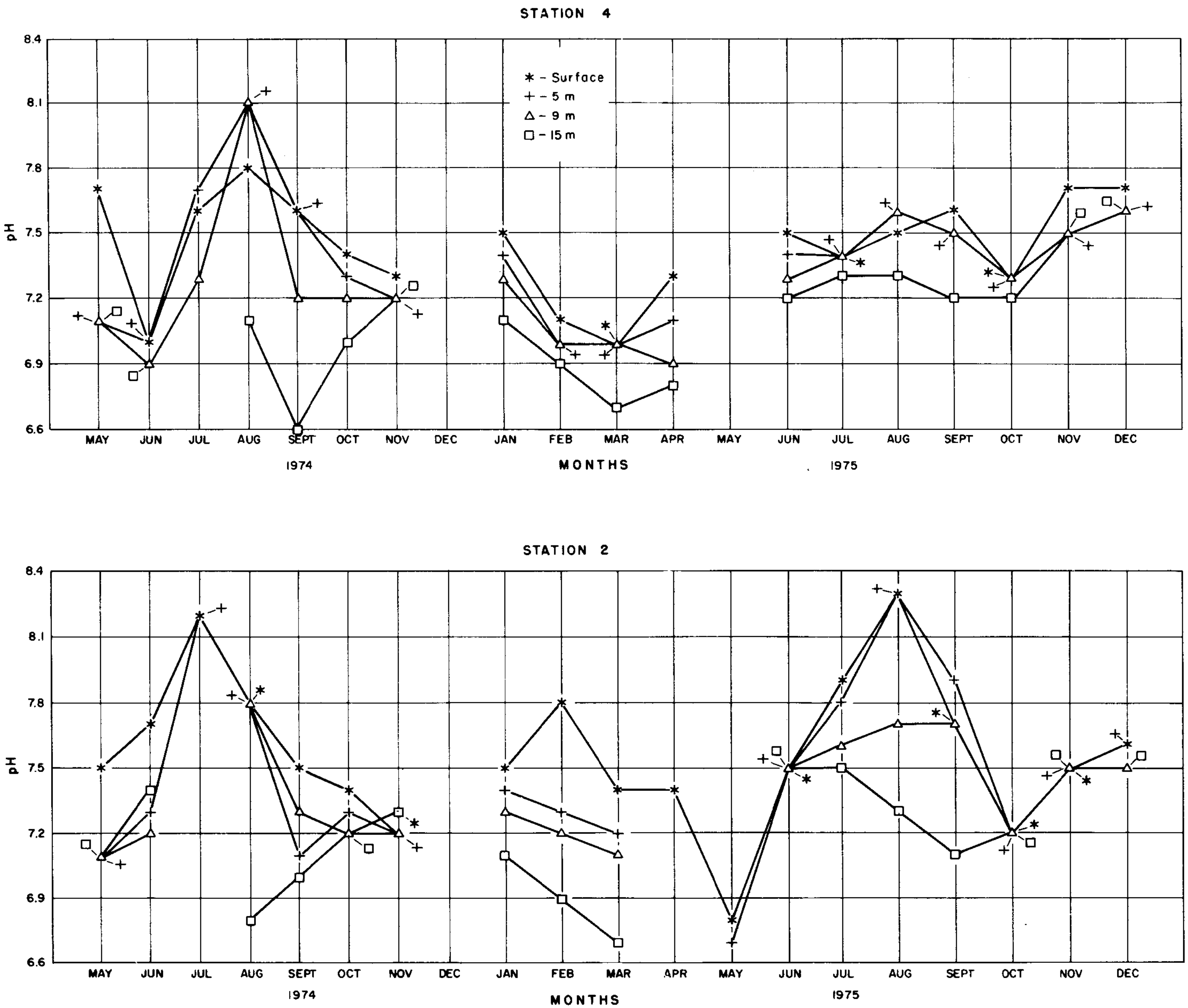


Figure 46.—pH at selected depths in Twin Lakes, 1974-1975.

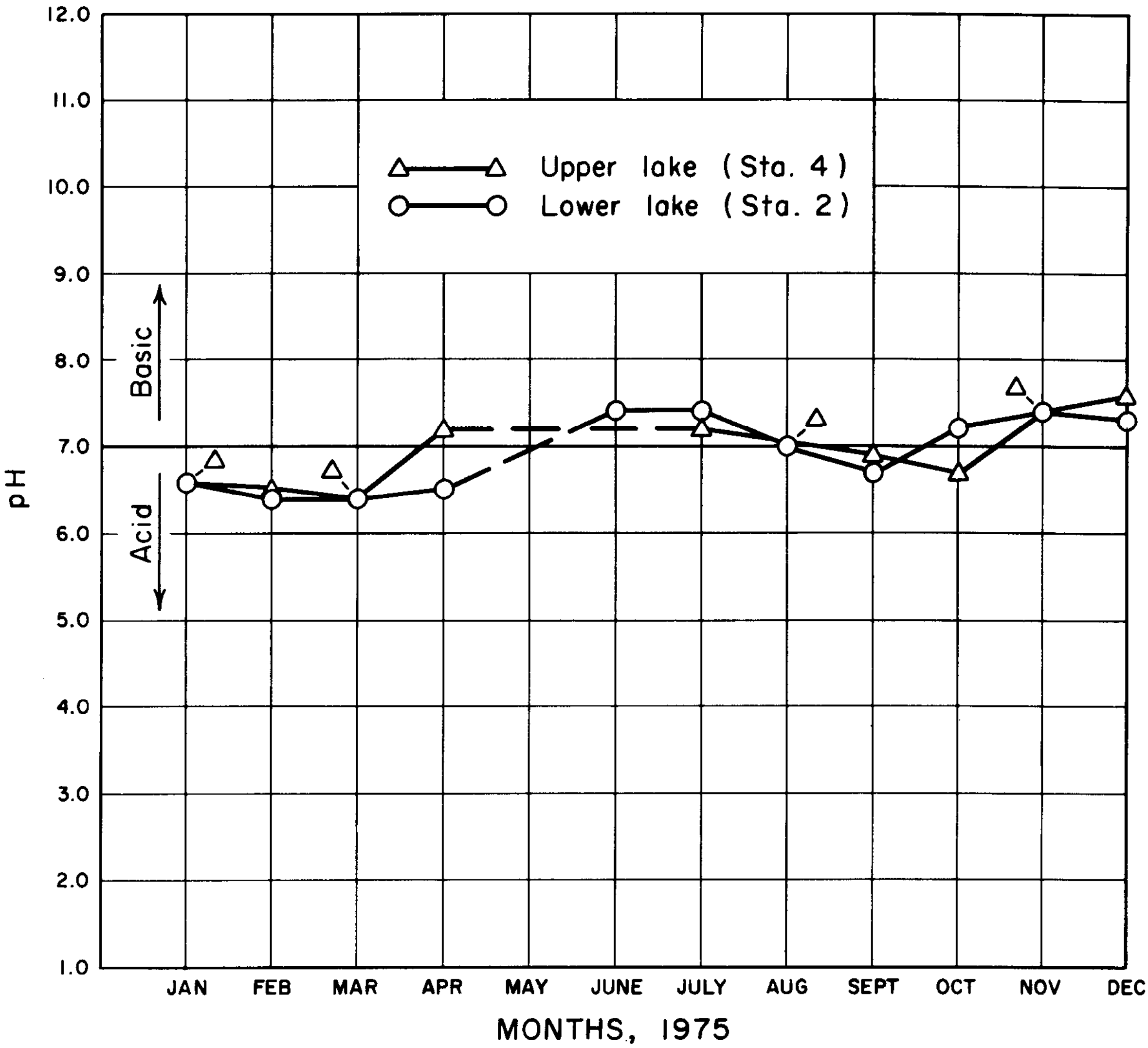
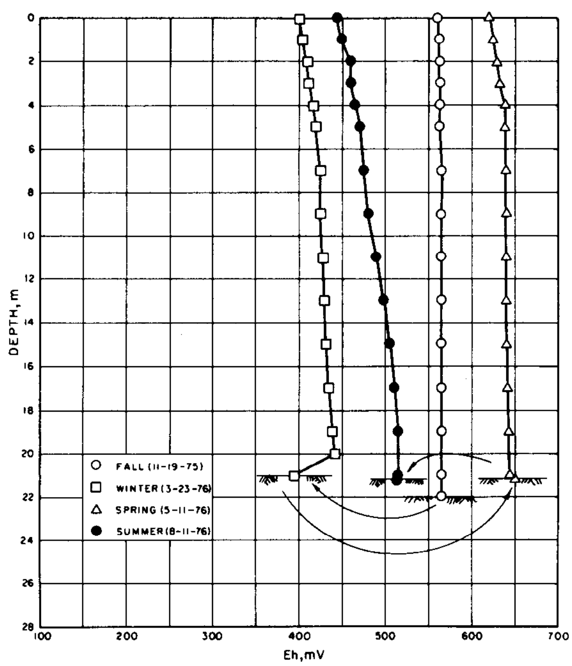
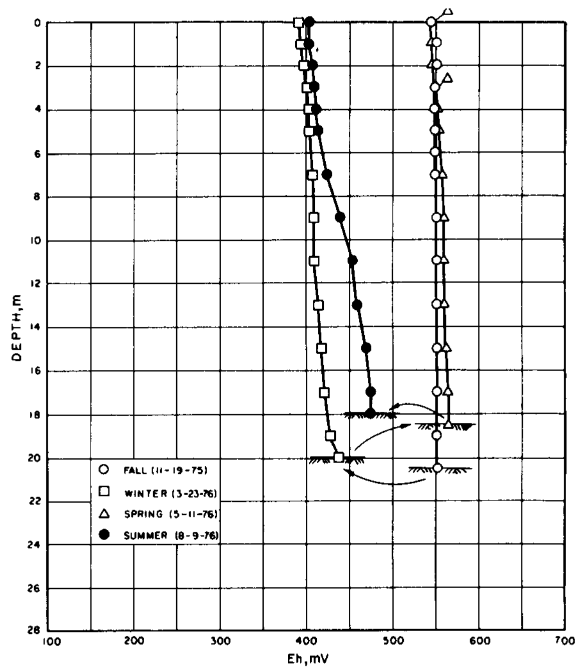


Figure 47.—pH of bottom water in Twin Lakes, 1975.



(a) Upper lake



(b) Lower lake

Figure 48.—Representative Eh profiles in Twin Lakes.

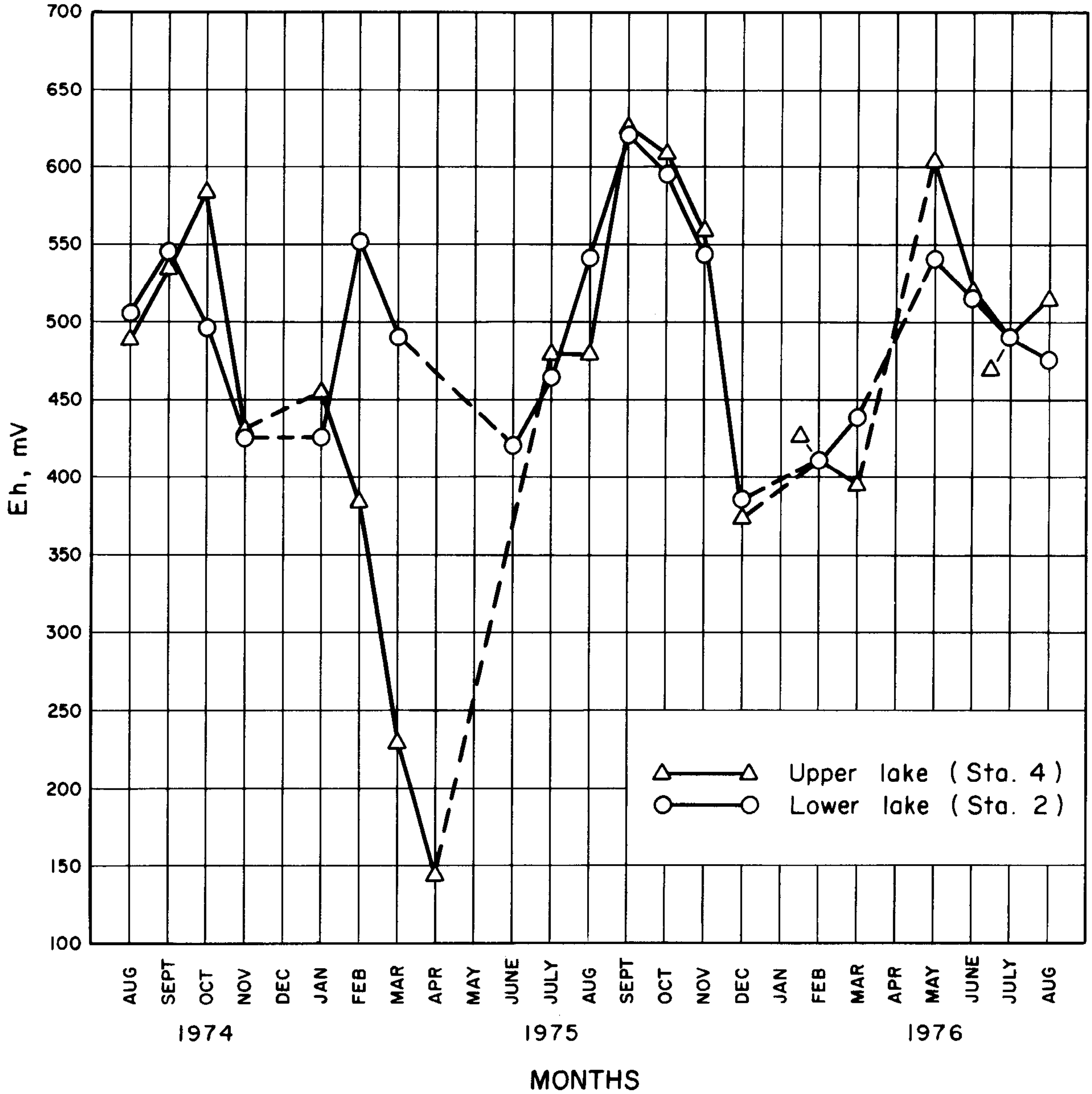


Figure 49.—Mean monthly Eh of bottom water in Twin Lakes, 1974-1976.

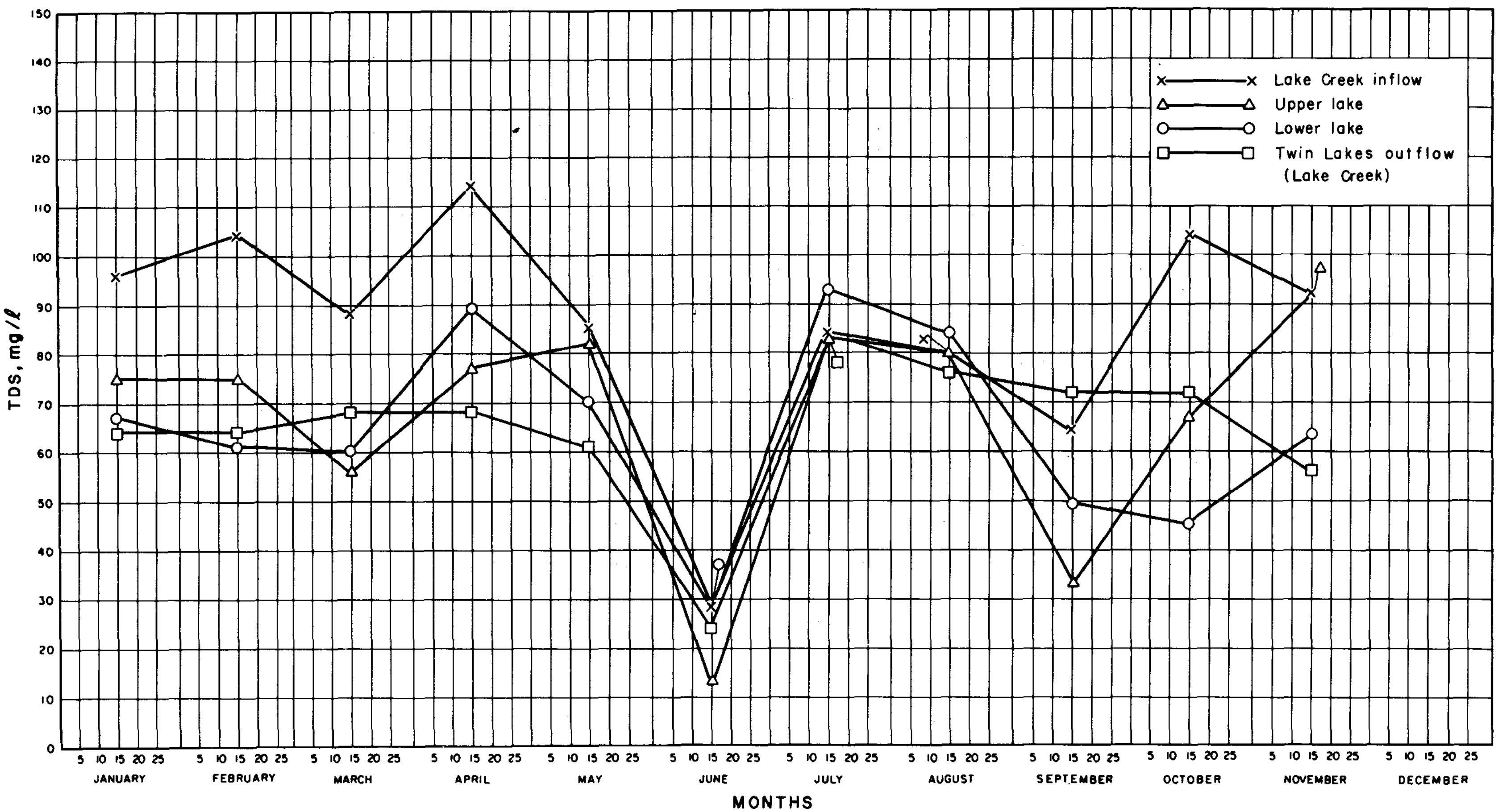


Figure 50.—Mean monthly TDS in Twin Lakes system, 1974-1975.

Twin Lakes is about 67 mg/*l*, while the lower lake averages about 68 mg/*l*.

A comparison of Twin Lakes with other lakes on the basis of TDS (table 7) would indicate both the upper and lower lakes to be relatively oligotrophic.

Table 7.—*Comparison of total dissolved solids**

Lake	TDS (mg/*l*)	Trophic status
Waldo, Oreg.	3.6	ultraoligotrophic
Twin Lakes, Colo.		
Upper lake	67.4	—
Lower lake	68.5	—
Great Bear, NWT, Canada	98.0	oligotrophic
Itasca, Minn.	185.0	eutrophic

*Data from Cole [22]

The annual cycle of TDS in the entire Twin Lakes system (fig. 50) reflects the strong influence of Lake Creek. Mean monthly TDS of both lakes and the outflow generally parallel that of the inflow, which is in turn inversely correlated with Lake Creek discharge ($r = -0.84$).

Mean monthly values of conductivity (specific conductance) for each component of the Twin Lakes system, during the period of April 1974 through May 1975, are graphed on figure 51. Cole [22] notes that for other than hypersaline waters, one would expect TDS to be directly related to conductivity. A comparison of figures 50 and 51, however, gives some rather unexpected results. While mean monthly conductivity of the Lake Creek inflow is directly correlated with TDS ($r = 0.80$) and inversely correlated with stream discharge ($r = -0.99$), the other components of the system exhibit a more linear trend that appears to be relatively independent of both TDS and stream discharge. The divergence between the TDS and conductivity graphs of the two lakes in June 1974 seems to indicate a change in the ionic species of the dissolved solids present. Heavy metals in the water at this particular time were at or below detectable limits (0.05 mg/*l*). The nature and causes of this suspected species shift have not been determined.

Major Ions

Mean concentrations of the major ions in the Twin Lakes system for the period of August 1971 through August 1976, are graphed on figure 52. The principal anion in both lakes, and their outflow, is bicarbonate (HCO_3^{-1}). Carbonate (CO_3^{-2}) is rarely detected in these waters because pH is usually below the level at which carbonate ions would be formed. The second most abundant anion in the lakes and outflow is sulfate (SO_4^{-2}). In the Lake Creek inflow, however, sulfate is slightly more abundant than bicarbonate. The principal cation in the entire system is calcium (Ca^{+2}).

Salinity, the sum of anions and cations, of each of the components of the Twin Lakes system is graphed on the extreme right of figure 52. The data indicate all these waters to be relatively dilute, with little significant difference in the abundance of major ions between the two lakes. Lake Creek inflow is about 50 percent more saline than the lakes, mainly because of its greater load of sulfates.

Typical seasonal profiles of the distribution of these principal ions with depth in the two lakes are on figure 53. Mean monthly concentrations of the same three ions in the Lake Creek inflow are plotted on figure 54. The lake data (fig. 53) indicate little in the way of stratification or seasonal cycles except for an increase in HCO_3^{-1} on the bottom of the upper lake during winter stratification. This HCO_3^{-1} peak is most likely derived from CO_2 produced by respiration in the organic bottom sediments (Mortimer [47], Cole [22]). Concentrations of the principal ions in Lake Creek (fig. 54) roughly parallel TDS (fig. 50) and conductivity (fig. 51), and reflect the diluting effect of high runoff in early summer and the concentrating effect of low fall and winter inflows.

Table 8 compares the ionic composition and salinity of Twin Lakes with those of five selected reservoirs on the Eastern Slope of Colorado and in Wyoming.

In its general chemical composition, Twin Lakes more nearly resembles Cabin Creek, Clear Creek, and Turquoise Reservoirs, all of which are located on relatively small streams in the mountains of Colorado. Pueblo and Seminoe Reservoirs are much larger impoundments on major plains rivers (the Arkansas and North Platte, respectively).

In summary, Twin Lakes resembles other Colorado montane lakes in chemical composition, the principal anion being HCO_3^{-1}, with SO_4^{-2} an important second. These two anions are about equally abundant in the Lake Creek inflow. The principal cation in both the lakes and Lake Creek is Ca^{+2}. Twin Lakes may be characterized as relatively soft and dilute calcium bicarbonate lakes.

Heavy Metals

Heavy metals of primary concern in Twin Lakes are iron, manganese, lead, zinc, copper, and cadmium. While water analyses have sometimes included

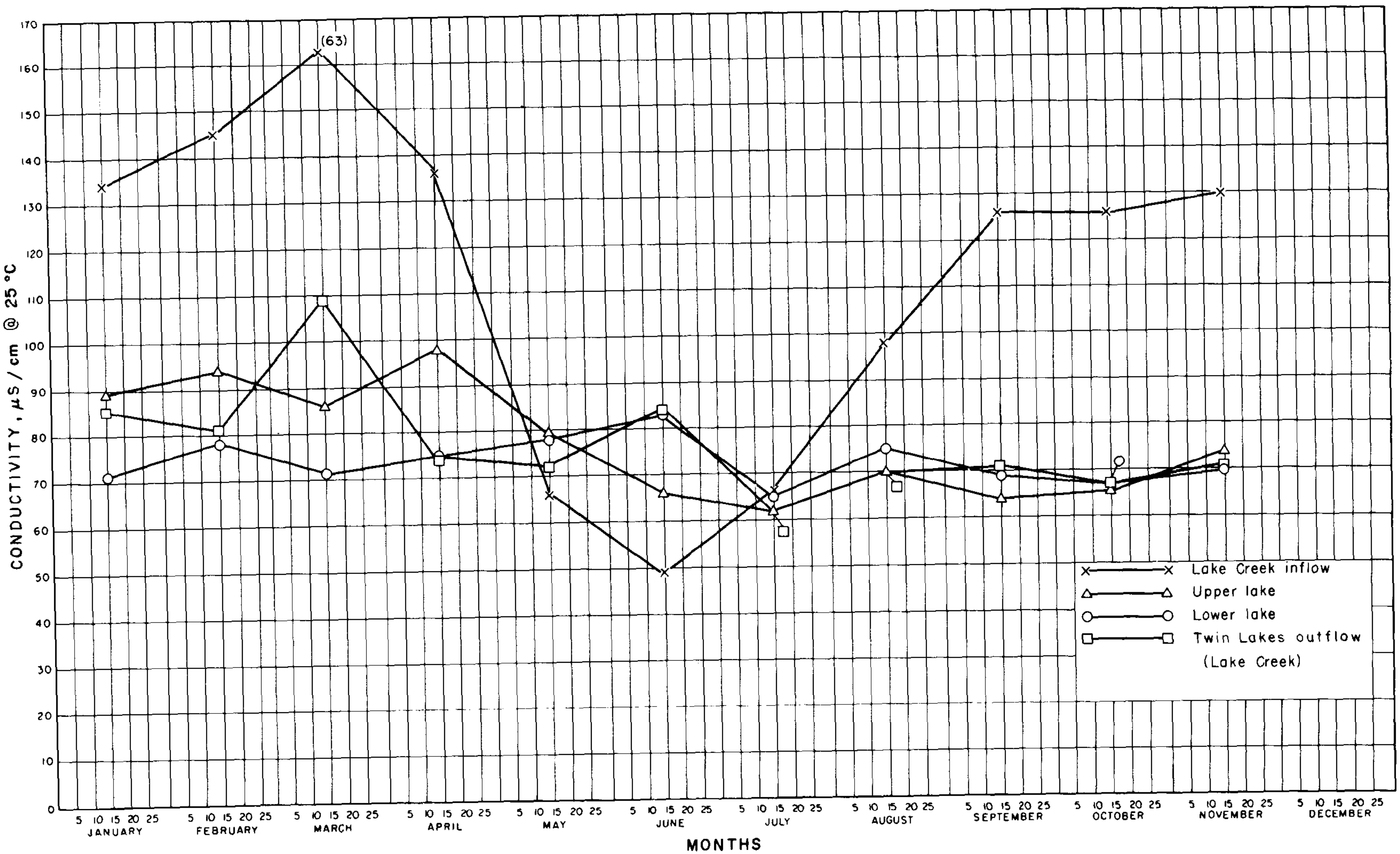


Figure 51.—Mean monthly conductivity of Twin Lakes system, 1974-1975.

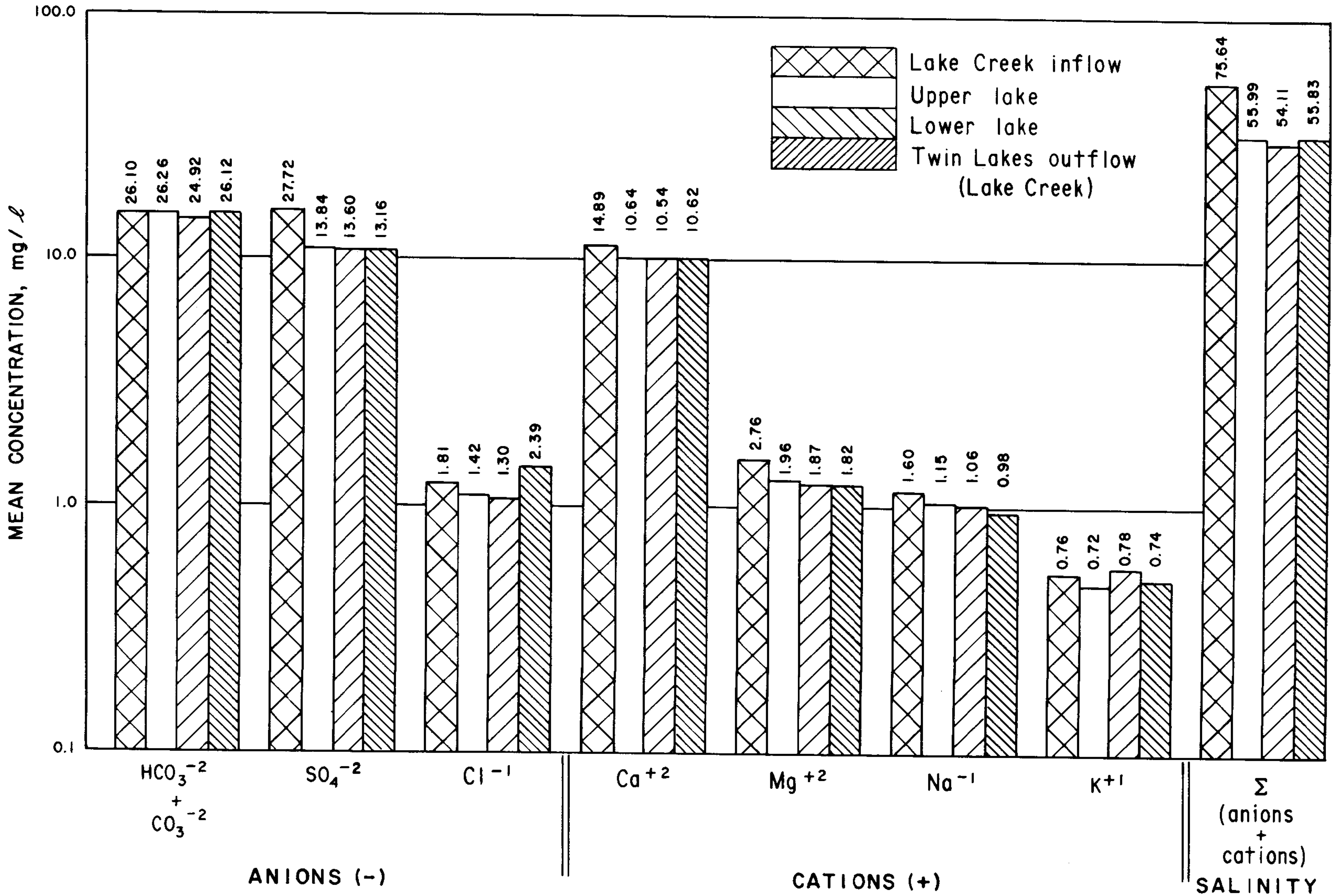


Figure 52.—Major ions in Twin Lakes system — mean concentrations, 1971-1976.

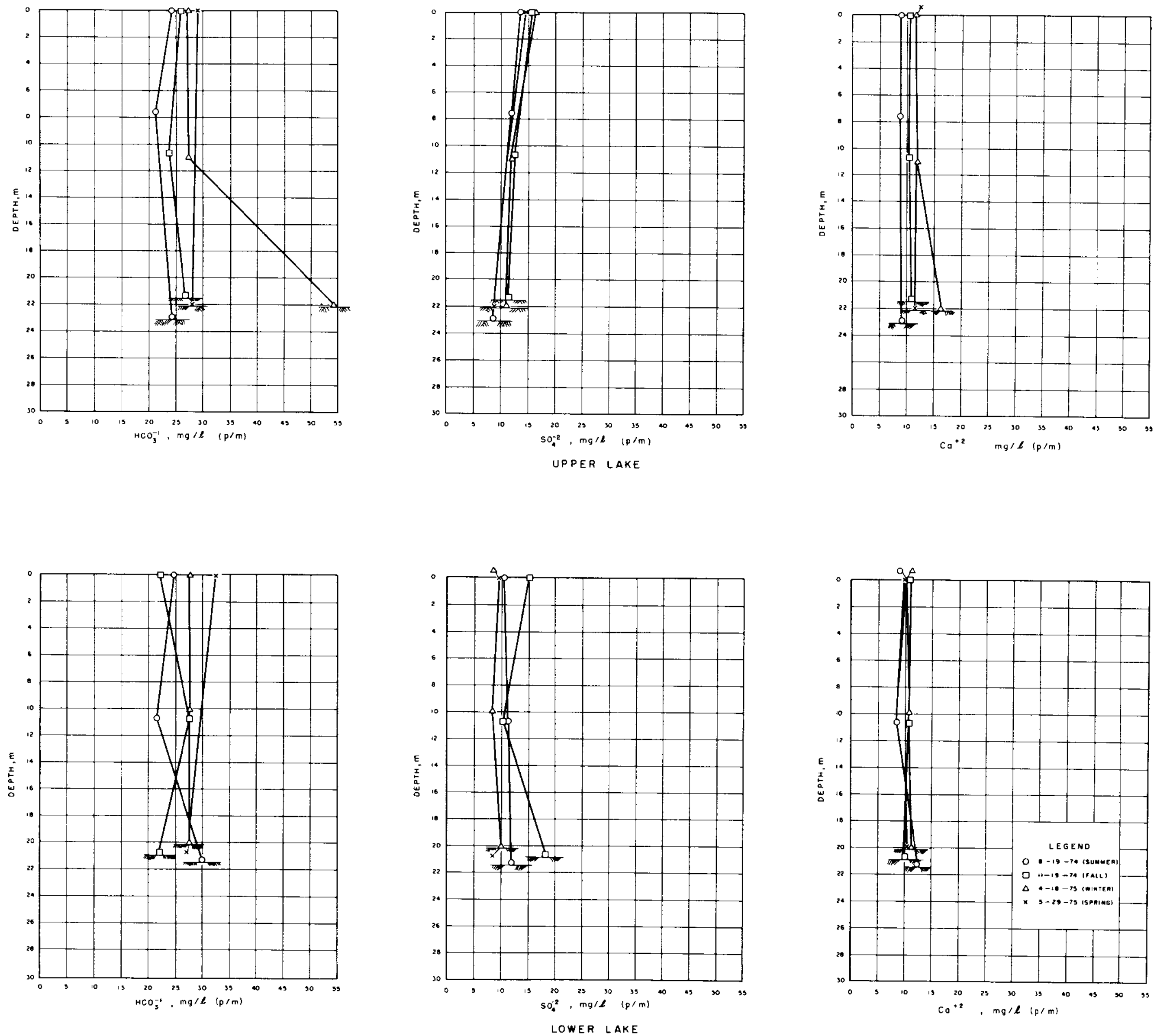


Figure 53.—Typical seasonal profiles of HCO_3^{-1}, SO_4^{-2}, and Ca^{+2} ions in Twin Lakes.

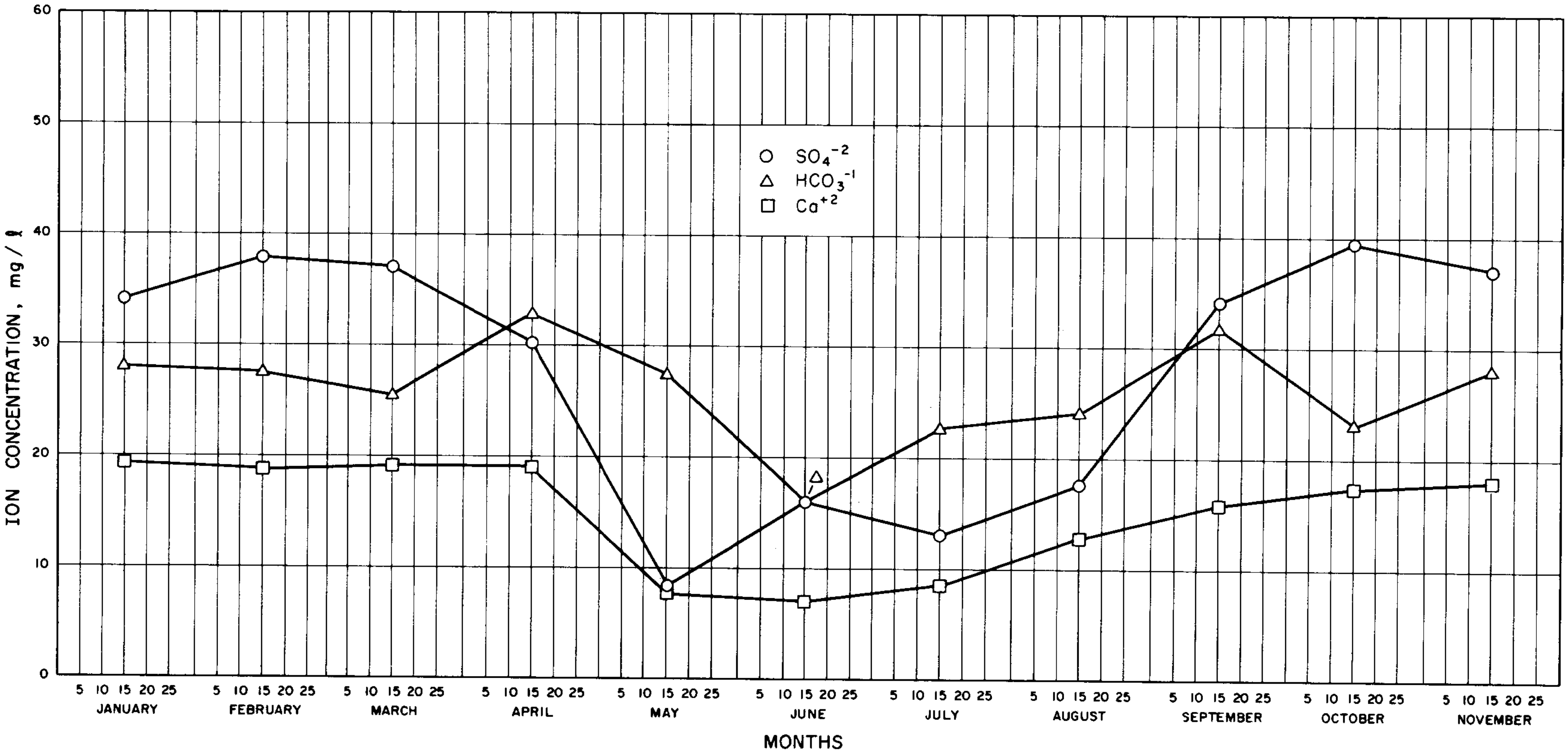


Figure 54.—Mean monthly concentrations of HCO_3^{-1}, SO_4^{-2}, and Ca^{+2} ions in Lake Creek inflow, 1974-1976.

Table 8.—*Comparison of ionic composition and salinity, mg/l*

Location	HCO_3^{-1} $+CO_3^{-2}$	SO_4^{-2}	Cl^{-1}	Ca^{+2}	Mg^{+2}	Na^{+1}	K^{+1}	Salinity
Twin Lakes, Colo.								
Upper lake	26.26	13.84	1.42	10.64	1.96	1.15	0.72	55.99
Lower lake	24.96	13.60	1.30	10.54	1.87	1.06	0.78	54.11
Clear Creek Res., Colo.	23.80	11.05	0.71	10.20	1.34	0.69	0.39	48.18
Turquoise Res., Colo.	15.90	2.52	0.71	4.20	1.07	0.23	0.39	25.02
Cabin Creek Res., Colo.	42.10	8.64	0.00	10.80	3.17	0.23	0.78	65.72
Pueblo Res., Colo.[1]	70.	136.	9.6	64.	16.	26.	3.2	325.
Seminoe Res., Colo.[2]	130.10	110.84	8.45	46.56	13.87	26.47	2.39	338.68

[1] Adapted from Herrmann and Mahan [35]

[2] LaBounty et al. [25]

molybdenum and silver, neither has been found in significant amounts. In the following discussion of heavy metals in the waters of the Twin Lakes system, all data are in terms of total metal concentration; that is, the dissolved and suspended fractions have not been separated.

Table 9 lists the mean and maximum detectable concentrations of the six major heavy metals in the waters of Twin Lakes. The extreme variability of these data is illustrated by the fact that in almost every case the maximum observed concentration is one to two orders of magnitude larger than the mean.

With the exception of manganese in the upper lake, table 9 indicates the mean heavy metals concentrations in Twin Lakes to be generally similar to observed concentrations in Turquoise, Clear Creek, and Pueblo Reservoirs, all in the upper Arkansas River Basin of Colorado. The upper lake, however, may be said to be relatively enriched in manganese.

Maximum observed concentrations of iron, manganese, copper, and lead in Twin Lakes closely resemble mean values recorded for these metals in the Arkansas River just below California Gulch, a mine waste polluted tributary near Leadville, Colo. In fact, the maximum manganese concentration recorded for the upper lake is nearly twice the mean at this point on the river.

Figure 55 presents a graphic comparison of mean heavy metal concentrations in the waters of the four major components of the Twin Lakes system. Iron and copper concentrations in the system follow a generally declining trend from the Lake Creek inflow, through the lakes, and into the outlet stream. Relatively high iron concentrations in the water column of the upper lake appear to be at least partially attributable to the influence of Lake Creek. Zinc and cadmium concentrations show relatively little difference from component to component of the system. Manganese and lead, however, display a very different trend from the other four metals in that lake concentrations are an order of magnitude greater than those in the inflow and outflow. Apparently, a significant proportion of these metals, when present in the waters of the lakes, arise from internal sources rather than from inflow. The grêater abundance of lead in the lower lake agrees well with the situation in the sediments where lead is also relatively more abundant compared with the upper lake. As noted previously, there is little difference in the relative abundance of manganese in the sediments of the two lakes. The larger quantity of manganese in the water column of the upper lake may be due to stronger reducing conditions mobilizing more of the accumulated metal.

Figure 56 compares the relative abundances of iron, manganese, copper, zinc, and lead in the inflow and both lakes on a mean monthly basis. Outflow data were too sparse for comparison on a monthly basis and have therefore been omitted from consideration here. Because of the extreme variability of the data, all comparisons on figure 56 are considered indicative rather than definitive. A trend in heavy metal concentrations generally parallel to the annual temperature cycle is evident in these data. The upper lake displays peaks in all five metals during the winter

Table 9.—*Comparison of Heavy Metal Concentrations in Water*

Location	Metal Concentration in mg/*l* (p/m)					
	Iron	Manganese	Zinc	Copper	Lead	Cadmium
Twin Lakes, Colo.						
Upper lake						
74-76 mean	0.367	0.210	0.024	0.019	0.028	0.0002
(maximum)	(2.530)	(2.500)	(0.300)	(0.09)	(0.100)	(0.0005)
Lower lake						
74-76 mean	0.144	0.084	0.015	0.014	0.043	0.0002
(maximum)	(1.5)	(1.200)	(0.048)	(0.07)	(0.130)	(0.0004)
Seminoe Res., Wyo.[1] (Aug/Sep '76)	0.196	0.027	0.009	0.003	**ND	—
Turquoise Res., Colo. (June/July '75)	0.299	0.026	0.031	0.018	0.025	0.0006
Clear Creek Res., Colo. (June '75)	0.383	0.022	0.020	0.009	0.008	0.0011
Pueblo Res., Colo.[2] (1974-76)	0.426	0.058	0.024	0.009	0.001	ND
*Arkansas River at California Gulch, Colo.[3]	2.66	1.35	3.33	0.06	0.2	—

[1] LaBounty et al. [25]
[2] Adapted from Herrmann and Mahan [35]
[3] LaBounty et al. [37]
*Area polluted by mine wastes.
**Not detected

stratification months of January through April, while the lower lake concentrations, except for lead, appear to peak both during winter and summer thermal stratification. With one exception, the overturn periods of June-July and November are characterized by a lack of detectable metal concentrations in the waters of either lake.

Iron in the upper lake is the single exception to this generalization and in this case the inflow would appear to be the major contributing factor.

Up to this point, all heavy metal concentration data have been cited and manipulated without regard to depth or location within the water columns of the lakes. Figure 57 represents typical seasonal heavy metal profiles in Twin Lakes for the period of September 1974 through May 1975. This period includes the end of summer stratification and continues through fall overturns and winter stratification to spring overturn. Inflow concentrations are included for comparative purposes.

Iron concentrations in the upper lake are always highest at the bottom of the profile. During September, this bottom peak is probably augmented by the plunging inflow carrying a relatively high iron content. In January, April, and May, however, inflow concentrations are relatively low and release of iron from lake sediment is the most likely cause of the bottom peaks. Dissolved oxygen concentration near the bottom was zero on April 18, 1975 (fig. 41) so that conditions were particularly conducive to release of metals from the sediment. Spring overturn had begun by May 29, and the lower concentrations on this date reflect oxidation and sedimentation of previously reduced iron compounds. Iron profiles in the lower lake, while similar to those in the upper, reflect the fact that oxygen depletion (fig. 42) and accompanying reducing conditions (fig. 49) are as extreme on the bottom of this lake during summer stratification as during the winter. Fall overturn was well underway in the lower lake on October 22, 1975, and it is likely that the high iron concentration at the bottom on this date was caused by iron compounds

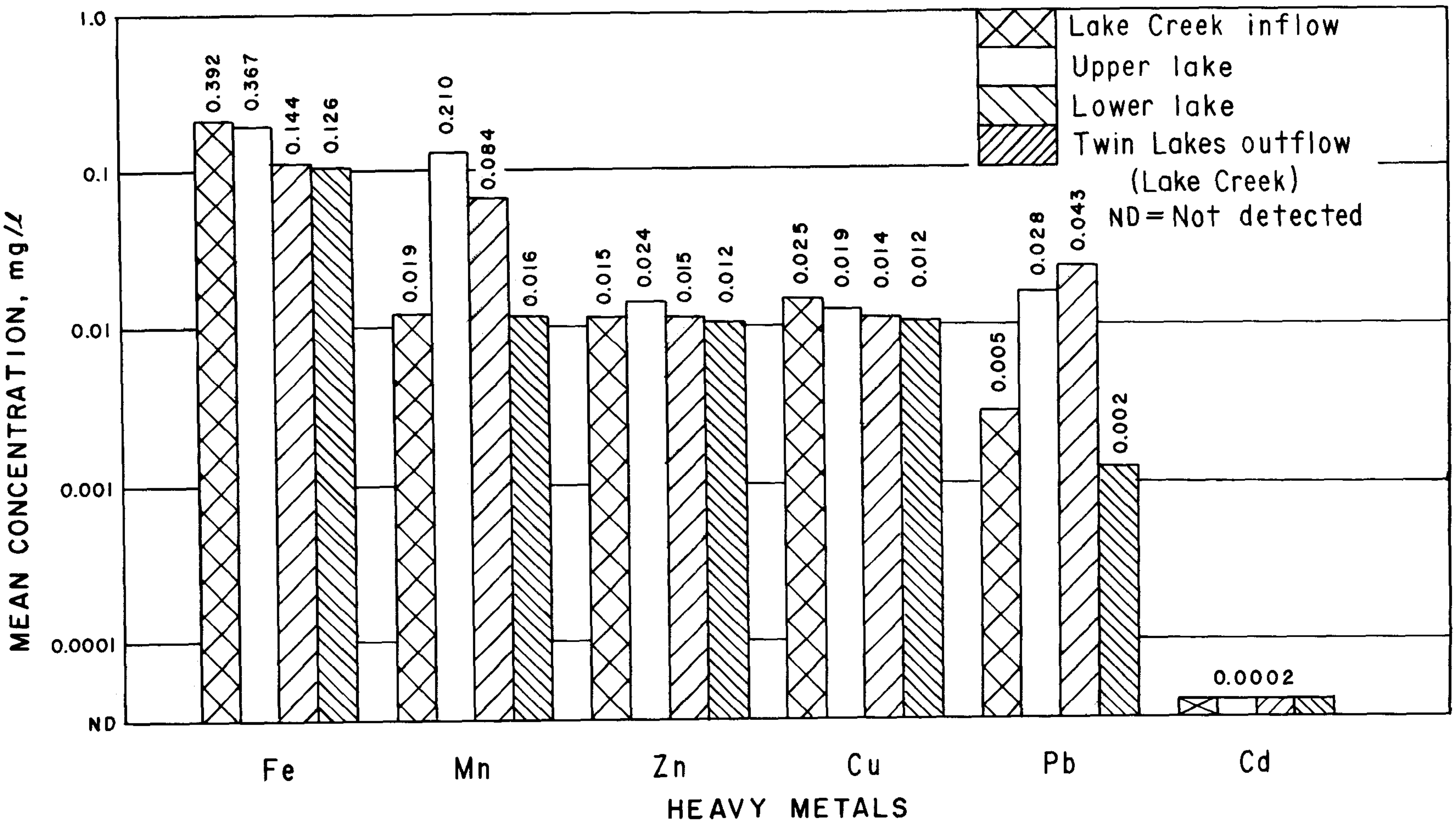


Figure 55.—Mean detectable concentrations of heavy metals in waters of the Twin lakes system, 1974-1976.

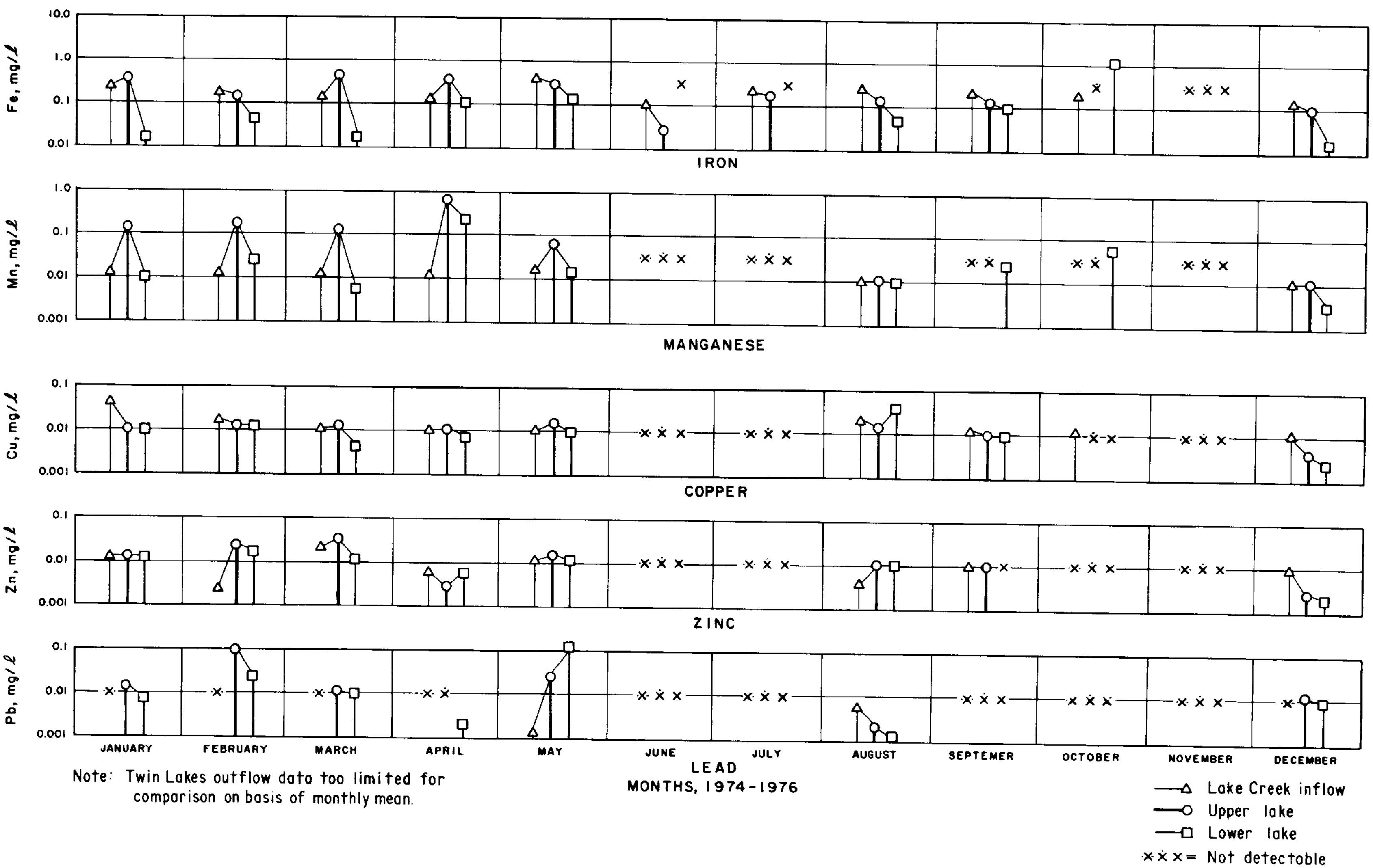


Figure 56.—Mean monthly detectable concentrations of heavy metals in waters of the Twin Lakes system, 1974-1976.

precipitating from the water column after summer stratification.

Manganese profiles in both lakes appear to confirm the observation made earlier, with respect to figure 55, that the main source of this metal in the water columns of both lakes is internal; that is, it is released from the sediments during summer and winter periods of oxygen depletion and low redox potentials. The copper and zinc profiles also reflect this situation, with bottom peaks being associated with negligible inflow concentrations. However, while iron and manganese concentrations peak at the height of winter stratification (April), copper and zinc peak at the time of spring overturn (May). Riley [48] noted that copper was most abundant in selected Connecticut lakes at the fall overturn following anaerobic summer conditions. Hutchinson [5] explained this observation by the fact that ferrous sulfide formed in the mud during stratification inhibits the solubility of copper, so that copper is only released when the sulfide has been oxidized at turnover. Something of this sort may be responsible for the later copper and zinc peaks observed at Twin Lakes.

Lead profiles are not included because this metal was found only sporadically in the waters of Twin Lakes (fig. 56). While mean detectable concentrations of lead were similar to those of zinc and copper (fig. 55), it was detected less than half as often in either lake. The data indicate that the primary source of this metal is the sediments and that it is mainly released during winter stratification.

To better understand the role of the lake sediments as a source of heavy metals in the water column, it is necessary to consider chemical interactions at the mud-water interface in some detail.

Available data on chemical interactions at the bottom of Twin Lakes for the period from April 1974 through October 1976, are plotted on figure 58. All parameters shown were measured or sampled within 1 m of the bottom, so that the plotted values are considered conservative estimates of conditions at the sediment-water interface (Hutchinson et al. [49], Pearsall and Mortimer [50], Mortimer [47], Hutchinson [5], Hayes et al. [51], Hayes [52], Hargrave [46], Cole [22]). To facilitate comparisons, D.O. concentrations have been converted to percentages of oxygen saturation, as explained earlier with reference to figure 43. Variations in pH have been accounted for by adjusting redox potentials to a standard pH of 7.00, thus converting Eh to E_7 (redox potential) (Mortimer [47], Cole [22]).

The clearest and most consistent trend in figure 58 is that of the percent D.O. saturation. As discussed earlier in the section on D.O., oxygen minima occur in both lakes during times of greatest thermal stratification. In the upper lake the observed winter minimum averages approximately 6 percent of saturation, while that observed during the summer averages about 45 percent. Comparable averages in the lower lake are approximately 26 percent during winter and 31 percent during summer. In both lakes, spring and fall overturns recharge hypolimnetic oxygen levels to at least 100 percent of saturation.

Two points should be emphasized when considering the seasonal pattern of E_7 in the bottom 1 m of Twin Lakes. First, D.O. is only one of several factors influencing E_7 (Pearsall and Mortimer [50], Mortimer [47], Patrick and Delaune [53], Hydrolab [45], Engler et al. [54]). Engler et al. [54] state, "Since there are a number of oxidation-reduction systems controlling the redox potential in a flooded soil, the disappearance of the oxidized component of one system, such as dissolved oxygen, will result in the potential decreasing rapidly to a new level at which other oxidation-reduction systems, such as those associated with manganese and nitrate, will again cause it to be stabilized at the lower potential." Conversely, when oxygen is restored to the system at overturn, E_7 may lag somewhat in its rise until reduced compounds in the water are oxidized (Rich [55]). Thus, the E_7 levels plotted on figure 58 display trends that follow, but do not strictly parallel, those displayed by percent D.O. saturation. The two trends, however, are particularly close at the extremes of oxygen depletion and supersaturation which occur on the bottom of the upper lake.

The second point is that the critical E_7, in terms of the cycling of substances between lake sediments and the overlying water is that which exists at the sediment-water interface (Mortimer [47], Hutchinson [5], Hayes et al. [51], Hargrave [46], Patrick and Delaune [53], Cole [22]).

Several investigators, beginning with Pearsall and Mortimer [50], have observed that E_7 levels drop sharply just below the sediment-water interface, resulting in an oxidized layer of varying thickness overlying strongly reducing sediments. Hargrave [46] for example, measured a mean decrease of 500 mV from the E_7 in the water just above the sediment surface to that at a depth of 10 mm within the sediments of Lake Esrom, Denmark. Patrick and Delaune [53] found that the thickness of the oxidized layer varies with the element in question and corresponds

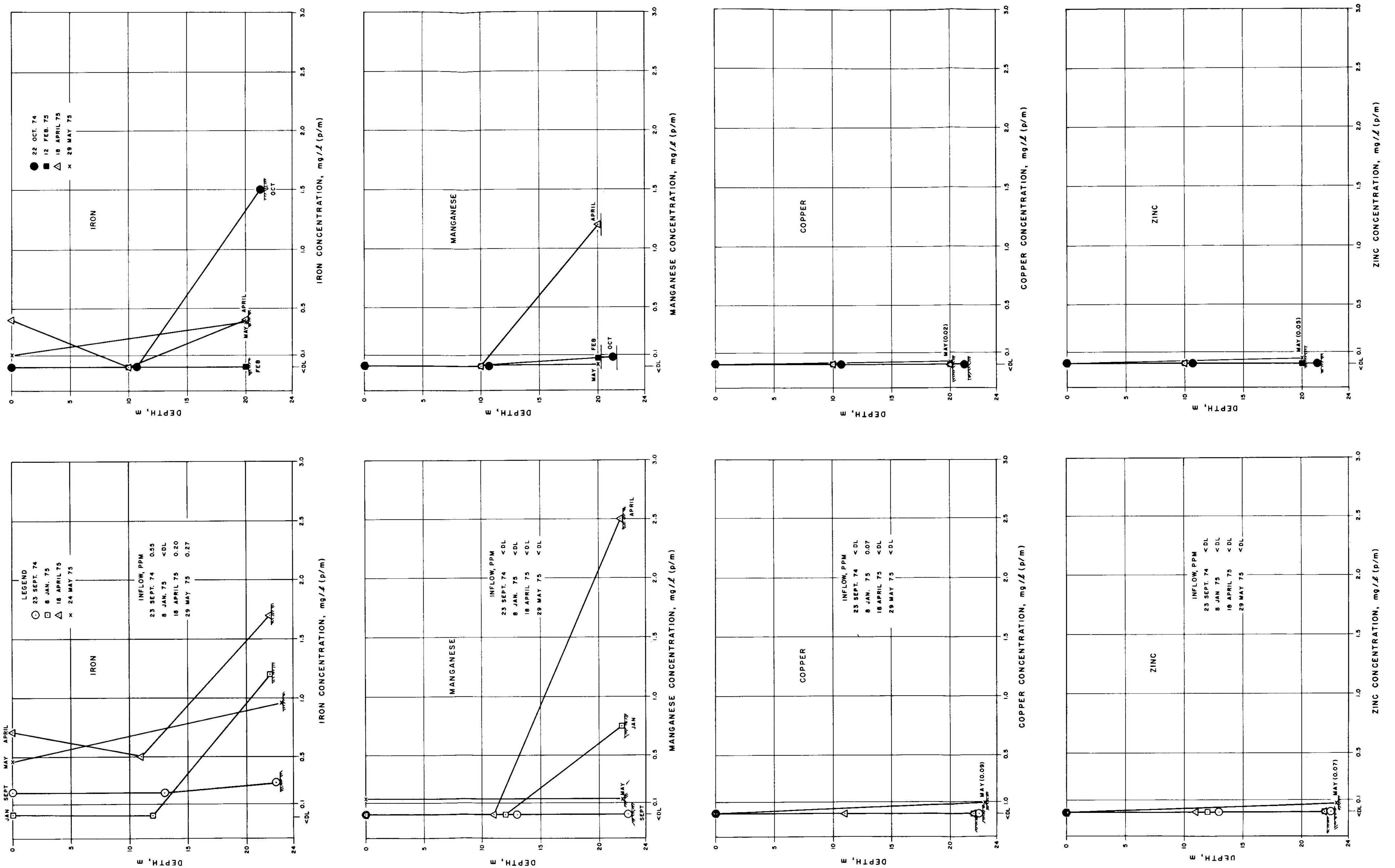


Figure 57.—Typical seasonal heavy metal profiles in Twin lakes, 1974-1975.

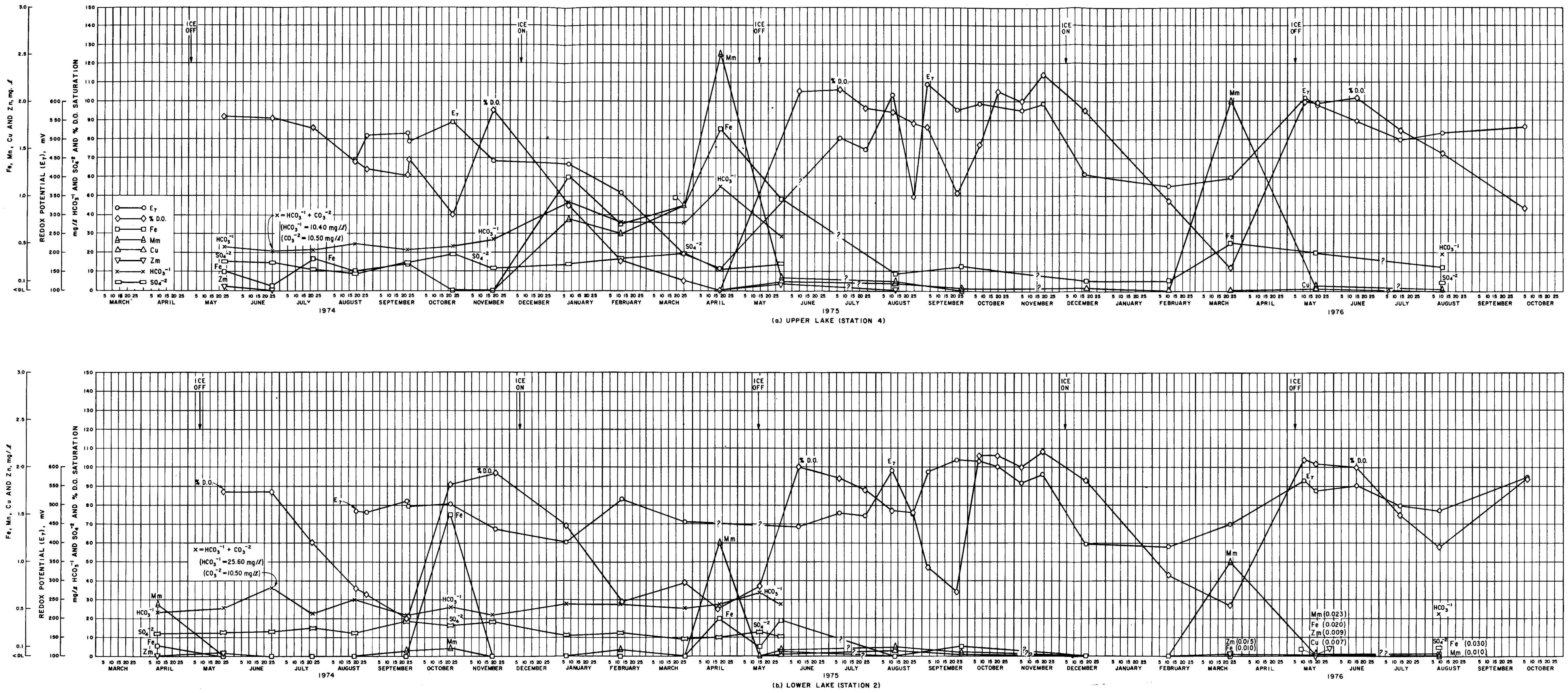


Figure 58.—Chemical interactions at the bottom of Twin Lakes, 1974-1976.

to the ease of reduction of compounds of these elements. Compounds of manganese, for example, are usually reduced at higher E_7 levels than are those of iron, so that the layer in which oxidized manganese compounds are present is thinner than the corresponding iron layer.

The relative ease of reduction of various compounds is determined by the position of their constituent elements in the electromotive series (Young and Porter [56], Frey [52], Weast [58]). In the case of the heavy metals considered here, the ranking in order of decreasing ease of reduction is manganese, zinc, iron, cadmium, lead, and copper. The actual potential at which the reduction of a particular compound of one of these metals will take place is a function of all the constituent elements and their chemical environment so that the above ranking is only a very general indication of relative mobility under reducing conditions. Mortimer [47], however, established the following E_7 ranges for some limnologically significant reductions:

Reduction	E_7 (mV)
NO_3^{-1} to NO_2^{-1}	450 to 400
NO_2^{-1} to NH_3	400 to 350
Fe^{+3} to Fe^{+2}	300 to 200
SO_4^{-2} to S^{-2}	100 to 60

The Fe^{+3} (ferric) to Fe^{+2} (ferrous) iron reduction is particularly important. Cole [22] and Hutchinson [5] consider the oxidized (i.e., ferric) iron layer an effective barrier to the diffusion of reduced substances from the deeper sediment layers into the overlying water. Reduction of the insoluble ferric compounds in the layer to soluble ferrous compounds destroys this barrier and allows reducing substances to diffuse freely into the hypolimnion of the lake. An E_7 of 200 mV at the sediment-water interface is, therefore, often considered to mark the transition from an "oxidizing" to a "reducing" environment in the hypolimnion (Mortimer [47], Patrick and Delaune [53]). The SO_4^{-2} (sulfate) to S^{-2} (sulfide) reduction, at or below an E_7 of approximately 100 mV, is also quite significant because heavy metal sulfides, including FeS (ferrous sulfide), are generally insoluble and tend to precipitate. The E_7 values plotted in figure 58, then, are conservatively high estimates of the E_7 levels at the sediment-water interface. An E_7 of, for example, 300 to 200 mV at 1 m above the bottom is very likely associated with an E_7 of 200 mV or less at the sediment-water interface and could thus be safely considered to indicate reducing conditions in the hypolimnion. As illustrated in figure 58, heavy metal peaks are usually associated with E_7 minima.

Iron is almost always present in the hypolimnion of the upper lake. The average concentration of iron is about 0.2 mg/*l* during periods of relatively high E_7 and is probably contributed by the Lake Creek inflow. During these same periods, other heavy metals are generally absent and HCO_3^{-1} (bicarbonate) and SO_4^{-2} (sulfate) concentrations average about 20 and 15 mg/*l*, respectively.

During the extreme reducing conditions of April 1975 (D.O. = 0 percent and E_7 = 155 mV), manganese peaked at 2.5 mg/*l* and iron reached 1.7 mg/*l*. Bicarbonate levels reached a high of 54.5 mg/*l*, indicating that oxidation of organic carbon to carbon dioxide was continuing in the anoxic bottom material (Rich [55]). Sulfate levels dropped from 19 mg/*l* in March to 11 mg/*l* in April, probably reflecting the beginning of some sulfate reduction at the sediment-water interface.

After ice-off in mid-May 1975, oxygen levels reached 105 percent of saturation. By early July, E_7 had reached 500 mV. At the end of May, manganese, iron and bicarbonate concentrations were down to 0.13, 0.96, and 28 mg/*l*, respectively. Sulfate had risen to about 14 mg/*l*. Copper (0.09 mg/*l*) and zinc (0.07 mg/*l*) appeared for the first time in detectable amounts at turnover and disappeared by midsummer.

The chain of events described for the winter of 1974-75 was repeated on a less severe scale during the next winter. Dissolved oxygen and chemical data from May 1974 also fit with observations in May of 1975 and 1976.

Chemical interactions in the lower lake, as plotted on figure 55, display generally similar, though less extreme, trends to those noted for the upper lake, with the exception of a strong iron peak in October 1974. Part of this peak may be a relic of oxygen depletion at the bottom of the lower lake during the summer of 1974. The increased manganese levels at the same time seem to indicate at least partially reducing conditions at the sediment-water interface, even though E_7 levels are high. It is also possible that some of this iron is suspended material, stirred up from the sediment by turbulence of fall mixing. In general, however, heavy metal concentrations in the hypolimnion of the lower lake are low except during winter stratification. Redox potentials in the hypolimnia of both lakes stay relatively high during summer stratification, even though percent D.O. saturation, especially in the lower lake, may drop to near winter levels. Perhaps the period of summer oxygen depletion is too short (1 month or less compared with 3 to 4 months in winter) to effectively eliminate the oxidation-reduction system associated with D.O., thus allowing E_7 levels to remain high.

The final consideration in this discussion of heavy metals in the waters of the Twin Lakes system is the ultimate source of the metals. As discussed above, the immediate source of most of the metals in the lake waters is probably the sediments, which have accumulated large amounts from the Lake Creek drainage basin. In an effort to locate more precisely the sources of these metals within the basin, two heavy metals surveys were carried out on the main stem of Lake Creek. Results of these surveys, which include both the fall low discharge and spring high discharge conditions, are listed in table 10.

Table 10.—*Results of Lake Creek heavy metal surveys*

(a) October 23, 1975 concentration, mg/l				
Site	Fe	Mn	Cu	Zn
N-3	0.25	<0.02	<0.02	<0.02
N-2	<0.10	< .02	< .02	< .02
N-1	0.20	< .02	< .02	< .02
S-1	4.90	.11	.18	.08
L-2	2.65	.03	< .02	.03
L-1	0.35	< .02	.02	< .02
(b) May 18, 1976 concentration, mg/l				
Site	Fe	Mn	Cu	Zn
N-3	0.450	0.024	<0.002	0.002
N-2	0.225	.012	.006	.005
N-1	0.250	.018	.004	.003
S-1	6.50	.044	.045	.017
L-2	2.25	.038	.022	.010
L-1	1.95	.044	.030	.020

Locations of the stream sampling sites are shown on figure 27. Descriptions of the sites are listed below.

Site	**Description**
L-1	Lake Creek below U.S. Forest Service gaging weir, Perry Peak Campground
L-2	Lake Creek below confluence of North and South Forks
S-1	South Fork just above confluence with North Fork
N-1	North Fork just below Twin Lakes Tunnel inflow
N-2	East portal of Twin Lakes Tunnel
N-3	North Fork above tunnel inflow

Results in table 10 consistently indicate the South Fork of Lake Creek to be the major contributor of iron, manganese, copper, and zinc. The South Fork at site S-1 was yellow-orange in color on both sampling dates and this color persisted as far as site L-2.

A survey of the same metals was done on the South Fork and its major tributaries in August 1976. Results of this survey are shown in table 11. Figure 27 shows the locations of the sampling sites; their descriptions are given below.

Site	**Description**
S-1	Same as S-1 in Lake Creek surveys; streambed stained yellow-orange
S-2	Unnamed tributary on east side of South Fork, approximately 1.9 km above site S-1; white deposit on rocks at stream mouth
S-3	Sayres Gulch just above confluence with South Fork; rocks in streambed stained red
S-4	South Fork just above Sayres Gulch inflow
S-5	McNasser Gulch just above confluence with South Fork
S-6	Headwaters of South Fork below Henschel Lake; water here streams down a slope incrusted with red, black, yellow, and orange deposits

Table 11 shows metal concentrations at site S-1 in August 1976 to be very nearly the same as those measured in the previous two surveys (table 10). The major contributor of all six metals surveyed was the small unnamed tributary which enters the South Fork at site S-2. Sayres Gulch (S-3) and the headwaters of the South Fork (S-6) both contained metal concentrations approximately equal to those measured at site S-1.

Samples of the crustal deposit at site S-6 were identified (Backstrom [59]) as extremely pure

Table 11.—*Results of heavy metal survey on South Fork of Lake Creek*

August 13, 1976 concentration, mg/l				
Site	Fe	Mn	Cu	Zn
S-6	3.150	0.048	0.180	0.037
S-5	0.030	<0.005	<0.002	.010
S-4	0.080	0.016	0.015	.010
S-3	2.90	0.050	0.235	.055
S-2	42.00	1.600	1.030	.870
S-1	2.400	0.050	0.120	.045

jarosite, a mineral with the chemical formula $K Fe_3 (SO_4)_2 \cdot (OH)_6$. Extensive red and yellow-stained slopes are evident, not only on Red Mountain, above Henschel Lake, but also on the high ridge east of Sayres Gulch. As there is little evidence of serious mining activity in the South Fork basin, heavy metals in this stream appear to have their ultimate origin in the leaching or erosion of naturally exposed mineral bodies at the headwaters of the South Fork and on the eastern flank of the basin.

GENERAL DISCUSSION

Summary of Present Conditions

Twin Lakes may be characterized as a pair of connected montane drainage lakes (Pennak [3]) of glacial origin (type 30a according to Hutchinson [5]). The lakes are relatively transparent, with mean light extinction coefficients of 0.63 m^{-1} for the upper lake and 0.47 m^{-1} for the lower. Both lakes have annual temperature cycles which place them in Hutchinson's [5] second-class dimictic category.

There is some depletion of D.O. at the bottom of the lakes during summer and winter stratification. Observed oxygen minima in the upper lake average approximately 6 percent of saturation in winter and 45 percent in summer; corresponding averages for the lower lake are 26 percent in winter and 31 percent in summer. The more extreme variation in oxygen minima in the upper lake probably results from the interaction of two main factors: (1) A significant deposit of woody debris on the bottom of the upper lake, which increases the hypolimnetic oxygen demand, and (2) The oxygenating influence of Lake Creek, which plunges to the bottom during summer stratification but is absent during the winter because of low flows and a lower relative density.

The sediments of Twin Lakes are classified as very fine-grained glacial rock flour (Klein [32]). Large accumulations of heavy metals, including iron, manganese, zinc, copper, and lead, have been deposited in these sediments by Lake Creek, the principal tributary. The ultimate source of these metals in Lake Creek appears to be naturally exposed mineral deposits on the South Fork.

During the prolonged period of winter oxygen depletion, reducing conditions (i.e., $E_7 \leq 200$ mV) develop at the sediment-water interface, causing large quantities of manganese and iron to diffuse into the water column. This situation may become especially intense in the upper lake during severe winters. The metals are precipitated when oxidizing conditions are restored at overturn.

Specific conductivity averages 77 μS/cm in the upper lake and 74 μS/cm in the lower. Total dissolved solids average 67 mg/l and 68 mg/l in the upper and lower lakes, respectively. Average pH values in both lakes are neutral to slightly basic (pH $\geq$ 7.0). Principal cation in Twin Lakes is calcium, with an average concentration of about 10 mg/l in both lakes. Major anions are bicarbonate and sulfate, with average concentrations of approximately 25 mg/l and 14 mg/l, respectively. In summary, Twin Lakes are soft, dilute calcium bicarbonate lakes (Cole [22]).

Speculation on Trophic Status

Mortimer [47] has described a situation existing in Windermere, in the English Lake District, that suggests strong parallels with the present condition of Twin Lakes. According to Mortimer, the North Basin of Windermere is significantly less productive than the South Basin. At the same time, sediments in the North Basin are much more reducing than those in the South Basin, because they contain considerable quantities of decomposing leaf fragments which are carried in by tributaries. The South Basin, which receives most of its inflow from the North Basin, contains relatively little of this allochthonous organic matter. Mortimer suggests some relation between greater reducing power of the mud and lower productivity in the North Basin of Windermere.

The secondary productivity of the upper lake is at present much less than that of the lower lake (LaBounty, et al. [13]). The upper lake also contains a large deposit of allochthonous organic matter and experiences more extreme winter reducing conditions than the lower lake.

Yoshimura's [60] description of Lake Busyû, Japan, also suggests some parallels with the upper lake. In this case, extreme summer reducing conditions, with complete oxygen depletion and abundant iron and manganese in the hypolimnion, occur in the bottom of a lake that has historically been relatively unproductive. Yoshimura attributes this state of affairs partly to an abundance of leaves in the sediments, but mainly to an extremely stable summer stratification, characterized by high surface temperatures and relatively little wind disturbance.

Juday's [11] work at Twin Lakes indicates that the upper and lower lakes were formerly more nearly equal in secondary productivity. He made no mention of the woody debris that is now so evident in bottom samples from the upper lake. It seems likely then, that the present discrepancy in secondary production between the two lakes is of relatively recent origin. The woody debris is probably a relic of the "marshy meadow" at the west end of the upper lake mentioned by Hayden [6] and Juday [11] which has since disappeared, apparently as a result of erosion caused by augmented flows in Lake Creek and more extreme fluctuations in lake level made possible by the alteration of the outlet and connecting channel.

Some observations (LaBounty, et al. [13]) during the present study may provide an insight into the way in which the disparity between the upper and lower lakes is maintained. Secondary productivity of the upper lake appeared to be increasing during the summers of 1973 and 1974. After the winter of 1974-75, however, with its extreme hypolimnetic anoxia and reducing conditions, zooplankton and benthic populations declined dramatically and remained at low levels through the summer of 1975. By the end of 1976, some recovery in population numbers was evident. It is possible that this type of "crash" in productivity occurs periodically in the upper lake, when longer and more severe winters encourage strong reducing conditions at the sediment-water interface. The authors hypothesize that the larger amounts of heavy metals released during these extreme reducing episodes are the mechanisms whereby productivity of the upper lake is limited. Some direct toxicity may be involved in the benthic populations (Hutchinson, et al. [49], Hutchinson [5]), but interference with a critical nutrient supply seems more likely to be the problem with the zooplankton.

Phosphorus is frequently a critical nutrient found in lake ecosystems in general (Hutchinson [5], Cole [22], Schindler [61]), and in mountain lakes in particular (Pennak [3]). The tendency of large amounts of iron to limit the availability of phosphorus for primary production in lakes has been demonstrated by several investigators (Hutchinson and Wollack [62], Hasler and Einsele [63], Hayes [52], Lee [64], Jackson and Schindler [65], Porcella, et al. [66], Koenings [67], Koenings and Hooper [68]). Hasler and Einsele [63] estimate that if the ratio of iron to phosphorus is 2:1 or greater in the oxygen-depleted hypolimnion of a lake, the entire phosphorus supply will be bound to oxidized iron at turnover and will precipitate as insoluble $FePO_4$ (ferric phosphate). Koenings [67] reports that flocculation (probably in the form of a protected sol of colloidal inorganic ferric iron) and subsequent precipitation of iron has been linked to phosphorus elimination from the upper productive waters of lakes of neutral to basic pH.

Data from Twin Lakes (LaBounty, et al. [13]) show phosphate phosphorus to be in short supply, probably near the 0.005 mg/l estimated by Pennak [3] as the average for montane lakes in north-central Colorado. Large amounts of iron and possibly manganese distributed through the upper lake at turnover after a severe winter could eliminate the available phosphorus supply and, thereby, drastically reduce primary productivity for the subsequent summer season. A reduction in primary productivity would in turn adversely affect secondary production.

To speculate further, Mortimer [47] has outlined a three-phase conceptual scheme for the evolution of lake productivity. During phase I, productivity increases at a very slow rate because the system is entirely dependent upon inflow for its supply of nutrients. After a period of time, enough organic material has been produced and sedimented to deplete oxygen in the hypolimnion during thermal stratification. The reducing environment thus produced at the sediment-water interface releases nutrients from the sediments and initiates phase II, a period of accelerated increase in productivity, with more complete cycling of plant nutrients within the system. Eventually this accelerated production of organic matter may induce a third, "sterile" phase where reduction at the sediment-water interface becomes so intense that iron is precipitated as insoluble ferrous sulfide, effectively sealing nutrients within the bottom mud. The first and third phases described here could probably be called "oligotrophic" and "eutrophic" phases, respectively, with phase II corresponding roughly to a "mesotrophic" condition.

Mortimer adds that not all lakes will necessarily pass through all three phases during their evolution. Some lakes that are very deep or are located in basins that are nutrient-poor may never evolve beyond phase I. Shallow, highly enriched lakes, however, may pass through all three phases very rapidly. Other lakes may be arrested in an earlier evolutionary phase even though the bottom sediments are in a highly reduced state because ample supplies of nutrients are continuously available from the drainage basin. Mortimer uses Hutchinson and Wollack's [62] term "trophic equilibrium" to describe this situation.

In the authors' opinion, the upper lake, the north basin of Windermere (Mortimer [47]) and Lake Busyû (Yoshimura [60]) comprise yet another category that might be called "trophic disequilibrium," in that these lakes appear to be in phase III without having passed through phase II. That is, allochthonous organic matter rather than internal production is responsible for the highly reduced, relatively unproductive state of these lakes. In the case of the upper lake, one could perhaps go a step further and term the condition "artificial trophic disequilibrium" since the allochthonous deposit is the result of human influence on the hydrology of the drainage basin.

Bergersen's [26] observation of a sudden increase in the A/C ratio (ratio of araphidineae to centrales diatoms) in the recent sediments of the upper lake would seem to fit the trophic disequilibrium hypothesis presented above. Bergersen stated that this increase in A/C ratio suggests "a distinct change from oligotrophic to eutrophic conditions at some time not too distant in the past." He attributes this shift to an increased organic import to the lake associated with the onset of heavy human activity in the basin in the late 19th century.

To summarize, the authors hypothesize that allochthonous organic matter recently (Juday [11], Hayden [6]) deposited on the bottom of the upper lake has increased the oxygen demand of the sediments to such an extent that they become highly reduced during long periods of thermal stratification and release large quantities of accumulated iron and manganese. These in turn limit the availability of phosphorus for primary production. The situation is particularly pronounced during severe winters when thermal stratification is prolonged and the oxygenating influence of Lake Creek is absent. The result is that the upper lake has been forced into an advanced eutrophic state (Bergersen [26], LaBounty, et al. [13]) without ever having passed through a mesotrophic phase (Mortimer [47], Hutchinson and Wollack [62]); that is, the upper lake is presently in a state of trophic disequilibrium.

If the hypothesis is correct, it should be possible to overcome this disequilibrium by supplying oxygen to the hypolimnion during the winter months, thus preventing the development of intense reducing conditions at the sediment-water interface. An attempt to do this will be undertaken during the winter of 1976-77. Molecular oxygen will be pumped through the ice into the hypolimnion of the upper lake in the form of very fine, low-energy bubbles that will quickly dissolve into the water without significantly disturbing stratification. If this treatment is successful, winter reducing conditions should be ameliorated and summer productivity gradually improved.

The lower lake should serve as a useful standard of comparison in this experiment. At present, the lower lake is generally oligotrophic to slightly mesotrophic in its evolutionary development (Bergersen [26], La Bounty, et al. [13]).

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ABSTRACT

The present study is an attempt to quantify the impacts of construction and operation of a pumped-storage powerplant on a montane lake environment by means of detailed investigations of the pre- and post-operation limnology of Twin Lakes, Colo. This report covers a 5-year study of the preoperation physical and chemical limnology of the lakes and includes a summary of earlier limnological work by such investigators as Chauncey Juday, David Starr Jordan, F. V. Hayden, and John Wesley Powell.

Twin Lakes are a pair of second-class dimictic, connected, montane, drainage lakes of glacial origin. Chemically, Twin Lakes are soft, dilute calcium bicarbonate lakes with large accumulations of heavy metals, including iron, manganese, zinc, copper, and lead, in the bottom sediments. During periods of thermal stratification, hypolimnetic oxygen may become depleted to such an extent that reducing conditions at the sediment-water interface allow significant quantities of these metals to diffuse into the water column. This condition is especially pronounced during severe winters in the upper lake, apparently as a direct result of the higher oxygen demand of allochthonous organic matter deposited on the bottom of the upper lake since the turn of the century. The authors hypothesize a state of "trophic disequilibrium" in the upper lake and describe an experiment to test this hypothesis by winter oxygenation of the hypolimnion which began during the winter of 1976-77.

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